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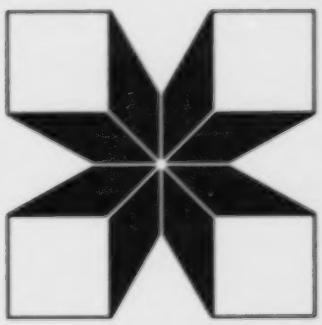

CANADA

SOLAR WATER DISINFECTION

PROCEEDINGS OF A WORKSHOP HELD AT
THE BRACE RESEARCH INSTITUTE,
MONTREAL, QUE., CANADA,
15 – 17 AUGUST 1988

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La présente série est réservée aux documents issus de colloques, aux rapports internes et aux documents techniques susceptibles d'être publiés plus tard dans une série de publications plus soignées. D'un tirage restreint, le rapport manuscrit est destiné à un public très spécialisé.

Esta serie incluye ponencias de reuniones, informes internos y documentos técnicos que pueden posteriormente conformar la base de una publicación formal. El informe recibe distribución limitada entre una audiencia altamente especializada.

IDRC-MR231e

SOLAR WATER DISINFECTION

Proceedings of a workshop held at
the Brace Research Institute,
Montreal, Que., Canada, 15-17 August 1988

Edited by

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Cosponsored by

Brace Research Institute, the International Development Research Centre,
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FOREWORD

During the past 12 months, discussions have been held with representatives of the International Development Research Centre (IDRC), Ottawa, Canada, the United Nations University (UNU), Tokyo, Japan and the Brace Research Institute (BRI) of McGill University, Montréal, Canada, on the possibility of bringing together various researchers from developing areas working on the subject of solar water disinfection. Both UNU and BRI have collaborated over the years on the operations of the Integrated Rural Energy Systems Association (INRESA) whose Secretariat is based at the Institute. One of the INRESA Network Projects involves the investigation of simple solar water purification techniques, designed to eventually provide an elementary means of destroying pathogenic water-borne bacteria for individual drinking water supply systems.

As IDRC has funded a number of studies in this regard, based on the original work of Professor Acra in Lebanon on solar water disinfection techniques for drinking water, it was felt logical to combine efforts and bring together researchers in both Networks around the world in this Workshop. This would permit a comparison of the results of their efforts with those generated by the INRESA Network and reported herein.

The principal objectives that have been established for this Workshop are:

a) a review of the state of the art of solar water disinfection;

b) the identification of research needs;

c) the development of guidelines on testing methodologies to provide for a better comparison of results between research projects; and

d) the development of field testing methodologies of water disinfection for the introduction of this technique at the village level taking account of relevant socio-cultural and economic considerations.

Both IDRC and UNU have contributed funding to permit the bringing of researchers to Canada and to cover the basic Conference expenses. They have also provided funds for the printing and eventual distribution of the Proceedings. The Brace Research Institute is providing the Conference management, the preparation of the Workshop documents and the editing of the Proceedings. A considerable amount of time and effort has been spent during the last six months structuring the Workshop, inviting the participants, arranging airfares, accommodation, lecture rooms as well as organizing all Conference arrangements. The Institute has also invited and paid the expenses of several delegates to participate in the Workshop.

The individual delegates participating in the Workshop have each prepared papers covering the principal findings of their research activities in order to contribute to the Proceedings. These papers are presented in a standardized format.

The Proceedings also contain summaries of the principal discussions and recommendations of the Workshop. An extensive bibliography has been prepared and included as an

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Appendix to the Proceedings. The reader is requested to refer to the Bibliography for any reference cited, particularly in those papers prepared by the INRESA Secretariat.

The Workshop is historical as this is the first time scientists and engineers from various countries would meet to discuss the use of solar radiation for water disinfection. This Workshop has been the combined efforts of many persons who have banded together to make a contribution to the future health and well being of millions of less fortunate persons around the world. The Workshop arrangements have been organized by a number of persons of the Institute whose names should be mentioned George Levesque, Wendy Ouellette, Vida Barrett, Angela Ives and Josef Ayoub. Thanks are due to Macdonald College Residence and Faculty Club for their assistance and cooperation.

T.A. Lawand

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PRINCIPAL FINDINGS OF THE WORKSHOP

The studies reported in these Proceedings were primarily directed to resolve the treatment of drinking water of those populations in developing areas of the world who:

a) collect their own water supplies from surface or ground water sources;

b) are without access to treated water;

c) may be interested in treating small quantities of drinking water for household requirements only.

It must be remembered that this is a very new field of endeavour and consequently the following findings are to be considered preliminary and will evolve in time.

1. In many places of the world (Colombia, Egypt, Nigeria, Peru and Canada), under different conditions of solar radiation, climate, water sources and level and type of bacterial contamination, the results of the research projects reported herein confirm the laboratory findings of Prof. Acra et al of Beirut, Lebanon, that is, that solar radiation exerts a germicidal effect on small quantities of bacterially contaminated water.

2. Solar Water Disinfection is effective when the intensity of solar radiation is at least 500 W/m^2 for about 5 hours.

   Like any other solar energy system, the Solar Water Disinfection technique does not seem to be very feasible during periods of continuous rainfall and heavy overcast conditions.

3. The disinfection process is effective in clear water. Turbid water significantly decreases the level of solar inactivation of bacteria. Therefore turbid water should preferably be subjected to pre-treatments like settling, filtration and possibly coagulation prior to solar disinfection.

4. Solar disinfection is not effective in highly contaminated water. Water with faecal coliform contamination of less than 1000 counts/100 ml can be decontaminated by this technique.

5. Solar decontamination works well when the water is exposed in clear, transparent glass or plastic containers.

6. The ultraviolet component of the terrestrial solar radiation appears to be mainly responsible for this bacterial inactivation, but visible wavelengths may also be involved in the process.

7. Water temperature variations below 40°C do not seem to play a significant role in the inactivation of bacteria in water. The Solar Water Disinfection technique has been tested with positive results at water temperatures as low as 12°C.

Additional Observations

1. Non-turbid water stored for long periods of time in dark opaque containers may eventually become almost totally free of pathogenic bacteria.

2. Bacteria once exposed for a short period of time to solar radiation appear to become more resistant to inactivation by solar radiation.

3. Containers with reflective interior surfaces permit solar decontamination of water.

4. A variety of pathogenic bacteria can be effectively inactivated by Solar Water Disinfection.

5. It should be remembered that turbid water cannot be effectively disinfected conventionally by chlorination without adequate clarification.

RECOMMENDATIONS

1. Further laboratory work is needed in order to investigate the effect of solar radiation on important pathogenic bacteria, viruses, protozoa and helminths in different parts of the world. The minimum solar radiation intensity and exposure time for each micro-organism have to be established.

2. Systematic laboratory studies are needed to understand the inactivation of micro-organisms by solar radiation and their probable repair and recovery mechanisms.

3. Carefully planned and executed pilot projects in different parts of the world are needed to verify the viability of the process and to assess the technical, socio-cultural and economical feasibility of introducing Solar Water Disinfection in developing areas.

4. Further research is needed to identify thoroughly the lower limit of solar radiation intensity below which the solar inactivation of bacteria in water may not be feasible. Depending on the type of bacteria and the level of contamination, a minimum exposure time with a given intensity must be established in order to achieve the desired level of water disinfection.

5. It is important to develop a simple field testing method in order to be able to assess the microbiological quality of the water with reasonable accuracy.

6. To avoid recontamination, small water quantities (one to two litres) should be treated by the Solar Water Disinfection process and then consumed directly from the container used for exposure to sunshine.

7. It is recommended that the Solar Water Disinfection technique should always be part of an extensive health education and sanitation program, as good sanitary practice and proper hygiene are necessary to avoid recontamination of the treated water within the family residence.

8. The solar inactivation process of other water-related pathogenic micro-organisms than those primarily studied herein should be thoroughly studied in-situ.

9. The research procedures for Solar Water Disinfection studies should be standardized. They should try to resemble as closely as possible the conditions found in nature. For instance, clean and sterilized water should be used for dilutions instead of distilled water, which could be used for baseline studies and for the assessment of the effect of turbidity.

10. In order to continue research and development in the Solar Water Disinfection field, a certain minimum amount of human, material and financial resources are necessary.

11. For disaster or emergency relief, larger scale systems should be investigated so as to determine the most effective conditions and procedures for them.

12. A study should be undertaken under given conditions of solar radiation and bacterial load to determine the optimum surface area to volume ratio of containers. The optimum path length of solar radiation through the exposed water sample should also be determined.

13. It is recommended that in carrying out experiments, the units in which the measurements are recorded should be standardized. For example, measurements of solar radiation in W/m^2 and estimation of total bacterial, total coliform and faecal coliform in counts/100 ml.

QUESTIONS DIRECTED TOWARD WORKSHOP PARTICIPANTS

During the discussion period and the Final Roundtable of the Workshop, a series of questions related to the Solar Water Disinfection Technique were raised to stimulate these sessions. Some of the questions were addressed while others were considered as important issues meritting further research. These questions are included in this section for information purposes and for establishing future fields of investigation. Four of these integrated fields were clearly differentiated to highlight the multi-disciplinary nature of this technique: microbiology, physics, materials/procedures and social-economic.

It is hoped that these questions will be useful for the people who did not attend the Workshop and who would be interested in undertaking research in this drinking water treatment technique.

Microbiology

1. What role does the initial count and type of bacteria play in the solar disinfection process?

2. Is there a rapid simple technique to ascertain water decontamination, especially at the village level?

3. Which bacteria should be studied in laboratory conditions to determine their sensibility to solar radiation?

4. If the process is interrupted, say due to cloud cover, half way through the disinfection procedure, can it be restarted the following day for the balance of the required amount of time, without bacterial regrowth?

5. Will the settlement of bacteria and suspended solids enhance their survival? i.e. Do we have to shake the bottles continuously or from time to time?

6. Does this simple disinfection process disinfect the inside of the container at the same time? (or does the container have to be disinfected separately to ensure that more tenacious bacteria do not enter the water being disinfected)?

7. Is there a simple way to predermine if a particular drinking water source will respond effectively to solar sterilization?

8. In what way does the volume of water to be decontaminated in a container, affect the efficacy of the process?

9. What are the proper storage procedures to prevent water recontamination?

10. Will sunshine inactivate the non-bacterial biotic contaminants of drinking water such as viruses, protozoa and helminths?

11. What is the remedy for decontaminating water containing non-biotic contaminants such as fertilizers, pesticides, acid mine draining, radioactive substances and industrial chemicals?

12. Does temperature play any role in the solar inactivation of bacteria?

13. Is a synergetic effect of high water temperature and ultra-violet (short wavelength) irradiance possible? If yes, what are the threshold values for temperature and irradiating wavelength?

14. Is it possible that a part of the incident (terrestrial) solar spectrum may help the bacterial growth rather than cause inactivation?

15. Do the processes of repair and reproduction of pathogenic bacteria continue during the exposure to sunshine? If yes, at what rate? Which factors decide the rate of reproduction and repair of these pathogenic bacteria?

16. What are the exact mechanisms of solar inactivation of bacteria?

17. Will sub-lethally injured pathogenic bacteria (non-detectable) recover if placed in a proper environment (human body)?

Materials and test procedures

1. What are the results of a comparative evaluation of MPN and Membrane Filtration methods in terms of:

    - applicability
    - limitations
    - availability of materials and equipment
    - cost(s)
    - type, quality and quantity of bacteria?

2. Is it necessary to use sterilized bottles for field and laboratory experiments?

3. Which is the correct method used to preserve and transport a natural water sample from the source to the laboratory?

4. In order to obtain a true and accurate sample of the natural water supply for laboratory testing, from a river, should the sample be taken very early in the day when there is no other activity, or during the day when people and animals use the water and stir up silt?

5. Do the measurements of temperature, solar radiation and bacterial counts have to be standardized in terms of equipment, units and test procedures? stipulate type of solarimeter used.

6. What type of containers should be used for SWD research purposes? glass or clear plastic? opaque, clear or coloured? volume? measurements?

7. Does each methodology (both in materials used and test procedures followed) conform to those materials, skills and conditions available to the end user? and tested in-situ?

Physics

1. How effective are traditionally used and locally available water containers, in transmitting solar radiation for water disinfection purposes?

2. Does the size and shape of a water container affect transmission of disinfecting wavelengths through water? if so how?

3. Is there an optimum surface area to water volume ratio for solar disinfection vessels, in order to achieve adequate disinfection?

4. What role does the thickness and type of container play in the efficacy of the technique?

5. How important is the orientation of the water container?

6. What type of container should be used when diffuse radiation component is high?

7. Is it possible to use reflective (inside) containers instead of transparent containers?

8. Taking into account that solar disinfection mainly occurs around noon hour, is it possible to use an open mouth non-transparent pail as a container, instead of a transparent one?

9. Is it quite practicable or cost effective to use solar concentrators for enhancing solar decontamination?

10. What is the effect of a dark or light surface immediately in front of and surrounding the water container? of a painted white surface, of placing a mirror in front, underneath or behind the container?

11. What is the minimum level of solar radiation intensity required in order to affect pathogenic bacteria destruction during normal daylight hours? What exposure time would this require?

12. What are the suggestions for disinfection of water during rainy seasons?

13. What guidelines can be given to utilizers during times of heavy airborne dust or during cloudy periods, with respect to exposure time?

14. What is more important the instantaneous value of solar intensity or the integrated value of solar radiation during the exposure period, or both, or some other related parameter?

15. From the spectrum (curve), how do we arrive at a conclusion that 350nm 500nm is the most lethal range?

16. What quality of filters have to be used (with tungsten lamp) in laboratory experiments?

17. What could be the equilibrium temperature of water in a typical container exposed to solar radiation at a certain place on a given day?

General and socioeconomics

1. What quality of water do poor people usually drink? Can we assume that it is necessarily dirty?

2. Who fetches the water? Which family member is supposed to take care of this task?

3. Will the SWD method of water treatment be socio-culturally acceptable, bearing in mind that local taboos, voodooistic beliefs and superstitions exist in many peasant communities?

4. Do the masses have sufficient incentive to do all this?

5. Assuming an optimum water container for disinfection purposes has been developed, is there sufficient local purchasing power to buy this better quality container?

6. What possible social factors may inhibit acceptability of this method in the rural areas of developing countries?

7. Bearing in mind that a few litres of drinking water are needed per person per day, is it necessary to disinfect enough drinking water in one day to satisfy only one family's needs?

8. Which local institutions may cooperate in the diffusion of this simple solar water disinfection technique particularly in:

   - Evaluating the quality of water sources being used?
   - Handling of water by the users?
   - In obtaining information regarding the morbidity and mortality rates caused by water-borne bacteria?
   - In collecting solar radiation data?
   - In training villagers to use this disinfection technique?
   - In co-ordinating and evaluating the progress of any such disinfection project?

9. Do local users undertake some form of filtration to lessen or remove the turbidity of drinking water? If not, what are the filtration techniques available to users in their locales?

OPENING REMARKS

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Solar Water Purification Definition and Limits

Solar radiation has been shown to inactivate and destroy pathogenic bacteria present in water. Some research teams have recently devoted their efforts to explore the possibility of using solar radiation for disinfection of bacterially contaminated water for drinking purposes. It must be stressed that this technique, at this stage, may only be used for disinfecting small volumes of drinking water required at the individual household level.

This Workshop primarily deals with these research programmes which examine the effects of exposing small quantities of water in suitable containers to solar radiation in order to ascertain the conditions under which this process will occur. The principal aim is to measure what happens when small volumes of water, intended solely for drinking purposes, are irradiated by the sun.

The effect of exposure on different types of bacteria in water are examined with a view to establishing guidelines which can eventually be distributed to extension officers in developing areas of the world.

The primary aim is to treat **small quantities of drinking water** only, on the premise that water used for cooking or in the preparation of hot beverages is generally disinfected through the boiling process. In essence, this would probably mean using the solar water purification technique to treat something in the order of 2 litres per person per day as a minimum or roughly 10 to 15 litres per family. Obviously, this amount will vary according to the location, the climate and the time of year, the degree of aridity of the area, the size of the family and other pertinent factors.

The research programmes covered in this Workshop have, of necessity, been directed to resolving the problems of the poorest segments of the populations living in developing areas of the world. These populations often do not have access to treated water supplies. In many instances, they do not possess sufficient fuel supplies in order to boil their water to effect adequate sterilization. Unfortunately, in some cases, it is not the custom to boil drinking water hence the spread of water-borne disease is heightened.

If solar radiation, which is universally available and which is, in this instance, essentially "free", can indeed meet the goal of disinfecting the drinking water of these less favoured populations the efforts undertaken by these and other investigational programmes will be well justified. The benefits of reducing disease resultant from the consumption of contaminated drinking water supplies are significant.

These water-borne diseases incapacitate the consumer, reducing their productivity, often shortening their lives and in general, have a deleterious effect on the entire community in which they are prevalent.

Oral rehydration therapy which has received considerable attention in the past decade is basically utilized as a simple, cheap, effective and acceptable treatment to counteract dehydration which is the most common cause of death amongst children suffering from acute diarrhoeal disease. The treatment consists of a water solution of sugar and salt given orally to replace both the water and electrolytes lost in the stools. However, the water utilized for the preparation of these oral rehydration solutions should indeed be safe to drink. UNICEF, amongst many others, first brought attention to the possibility of utilizing solar radiation for the disinfection of drinking water and oral rehydration solutions. In 1984, they published a booklet by Acra et al. under the above subject entitled: "Guidelines for Household Application in Developing Countries" which presents the work of Prof. Acra and his associates at the American University in Beirut, Lebanon.

The preliminary findings of this work show that for disinfection purposes, the most effective solar spectral band appears to be the ultraviolet, especially the near U.V. (300-400 nm) with an optimum at 357nm. The angle of incidence is important and an inclined receiver, facing the Equator, will receive the most irradiation. Even though scattered radiation is still effective, direct irradiation seem to be the best. Clear glass, polystyrene, polyethylene and methacrylate transmit U.V.-radiation above 300 nm fairly well. In clear water the attenuation of solar energy (300-500 nm) is less than 5% per metre.

Professor Acra and his team found that with a 95 minutes exposure to sun (always between 09:00 hours and 14:00 hours in Beirut) 99.9% of the faecal coliforms of a contaminated water sample were killed (300 minutes were required for inactivating 99.9% of the total bacteria).

Other tested microorganisms and their inactivation times measured at the American University of Beirut were:

P. aeroginosa 15 min.
S. flexneri 30 min.
S. typhi 60 min.
S. enteriditis 60 min.
E. coli 75 min.
S. paratyphi 90 min.
Coliforms 80 min.
Aspergillus 3 hrs.
Candida 3 hrs.
Geotrichum 3 hrs.
Penicillium 8 hrs.

Prof. Acra has indicated that the solar disinfection of water can be utilized for Oral Rehydration Solutions (ORS). This should be done every day or every other day and the containers should be kept closed and clean. Labels have to be removed and shadows and turbid waters have to be avoided. Special care is recommended against recontamination and a minimum exposure time of 2 hours at full noon sun is generally needed. Water containers should be placed in an unshaded space where the sunlight is not obstructed

by houses, trees or bushes, and they should be spread out as wide as possible to avoid shadows.

The germicidal effect of the solar radiation is altered by the turbidity of the water sample, the color of the container (the best seem to be transparent or light blue), the wall thickness, the shape (best are the round or cylindrical) and the local climatic conditions.

It is therefore possible to disinfect small quantities of household drinking water on a routine basis if clean, transparent containers filled with water are placed in full sun in the morning and left exposed for several hours. These exposed containers now containing disinfected water may either be left in place overnight and allowed to cool, or transferred indoors for eventual consumption.

Earlier research has indicated that in an emergency, when a family has run short of disinfected water, an exposure of two hours or longer around noon under high solar radiation levels, should be adequate for disinfection. It is not practical to attempt the purification process during periods of heavy rainfall and/or rainfall.

Discussions were held with UNICEF officials in 1985 to determine the state of the art in this particular field. What was ascertained was that they wished to see significantly more research undertaken into this particular technique for water treatment. As a result the UNU embarked upon a network programme of solar water purification, administered by the INRESA Secretariat, located at the Brace Research Institute.

One of the main problems of solar water purification is in its basic simplicity. Unfortunately, when a system is simple, liberties are sometimes taken and as a result the possibility of error is more likely. In addition, what is in effect a simple system to utilize in the field may be a complex interaction of physical, chemical and biological mechanisms which often are not clearly understood.

Similarly, a simple case in point is the solar still in which small quantities of saline water are distilled into fresh water. Many simple solar stills have been built and are utilized around the world. They are extremely simple to build and to operate. However their mechanism of operation is highly complex. Radiative, convective and conductive heat transfer are taking place simultaneously and interactively with mass transfer evaporation, condensation and crystallization. Many theoretical and experimental studies have been undertaken to determine the complicated nature of this simple single effect distillation process.

In a parallel manner, exposing small quantities of slightly contaminated water to solar radiation is also a complex interaction of the following parameters:

a) the level of contamination of the water;
b) the type of bacterial contamination in the water;
c) the turbidity of the water;
d) the type, shape and size of the water container;
e) the intensity (and the spectral distribution) of solar radiation and whether it is direct or diffuse;
f) the angle at which solar radiation strikes the water container;

g) the transmissivity of the walls and lid of the water container for the solar radiation, with particular reference to those wavelengths which have a germicidal effect on the bacteria;
h) the transmission of these germicidal wavelengths through the water;
i) the length of the path traversed by the radiation in the water and the effect of reflectivity of the inside wall of the container on these wavelengths;
j) the temperature of the water; and
k) the acquired resistance of already exposed bacteria.

There are, no doubt, other factors as well. In order to fully comprehend this technology, it is essential to understand clearly the mechanisms that are being undertaken. It should be made perfectly clear at this stage that the research undertaken to date has not adequately addressed each and every one of the above parameters. This will take years of study of an academic and basic nature. It will require interdisciplinary teams and will necessitate the expenditure of considerable sums of money.

The research conducted so far on this topic in different parts of the world, deals primarily with the following factors:

1) the quantity of water being exposed;
2) the total amount of solar radiation measured, usually on the horizontal, during the exposure period;
3) the temperature of the water and the air; and
4) the total and (usually) the faecal coliform bacterial counts at the beginning, during and at the end of the experiment.

Some of the basic questions that have not been fully addressed in this research are:

a) the identification of the exact wavelengths or wavelength bands of solar radiation which are responsible for the purification process;
b) the possibility of variation of germicidal solar wavelengths with type and concentration of different bacterial colonies in the water; and
c) the exact mechanism of inactivation, resistance and destruction of the bacteria.

There are many other unresolved questions to which researchers can apply their efforts. Indeed, even from an applied research point of view, the research undertaken to date has attained some of its objectives but obviously not all. It is not yet possible, for example, to give relatively precise instructions as to the size and shape of containers, the length of exposure in hours, the level of solar radiation and the degree of contamination of the water. This will have to be done in terms of generalities, at least initially. It would also be extremely useful if a very simple test could be developed so that the householder (and indeed the researcher at this stage in the field) could ascertain whether the water is safe for drinking or not. That is, whether all pathogenic bacteria have been indeed eliminated.

It should not be expected that the availability of solar radiation on a horizontal surface, for disinfection purposes would be constant throughout the year. Indeed there are significant diurnal and seasonal variations in the levels of solar intensity in various wavelength bands. Are these variations sufficiently significant to affect the rate of solar water disinfection? Detailed comparative studies monitoring the intensity of specific germicidal wavelengths have to be systematically undertaken. It might

therefore be surmised that in most locations, the periods of the year with higher solar intensity might have greater potential for more rapid and effective solar water disinfection. Surely, this has to be proven experimentally in a most rigorous scientific manner to be conclusive.

Therefore, to recapitulate, this study is primarily directed to resolving the problems of those populations in the developing areas of the world which:

a) generally collect their own water supplies either from surface or groundwater sources;
b) normally have no access to other water purification techniques such as chlorination, U.V. treatment, ozonation or boiling, etc.; and
c) normally are treating water for their personal and family use rather than larger systems for community use.

It should be mentioned that some work has been done to apply this technique to larger scale or community based systems. This is interesting and merits attention. However, it should not detract from the **primary** purpose of the exercise, that is, the necessity of assisting the poorest and least developed sectors of the global society, which number in the hundreds of millions, to develop a simple safe technique for treating their otherwise untreated drinking water.

Some knowledge has indeed been acquired. It can be confidently stated at this stage that the technique works. Exactly how it works and precisely what mechanisms interact are still yet not clearly understood. It should never be forgotten that this field, as stated above, is directed to the requirements of the poorest populations of the world. The field is still in its infancy. This does not mean that the literature, especially in the biological sciences, is not replete with references to the natural disinfection of contaminated water in the environment. These references, generally go well beyond the scope of the investigations, in this particular project.

It is essential that the constituency of researchers be vigilant not to be immediately lured into over-complicating this technology at this stage of the development in the field. It is much easier and in some instances, neater, to undertake research and to make applications for treating the water supply for more established, organized and wealthier individuals, families and communities in the world. However, it is much more difficult and demanding to undertake research to offer a potential alleviation for the purification of the water supply for the large, poorest segment of the world's population. It requires a good grasp of science, technology and a dedication to resolving part of the problems of this sector of the world's population.

Hopefully during the Workshop, it should be possible to:

a) establish a systematic approach to various measurements involved in this technique;
b) agree upon developiing proper methodologies to conduct field trials; i.e. to identify when field trials should be initiated and what type of partners should be selected for the field trials; and
c) establish guidelines and priorities for further research in this area.

OPENING REMARKS

Alex Redekopp

Health Sciences Division, International Development Research Centre, Ottawa, Ontario, Canada

It is a great pleasure for me to welcome you to this Workshop on behalf of IDRC, the co-sponsor. I wish you all a most successful week. Tom Lawand and his staff have been very hard at work for many months to make this Workshop a success. It's up to all of us now to show that we can live up to Tom's expectations.

In his opening remark, Tom has set the stage technically for the Workshop and has brought us up to date very quickly on what has been done in this field and what remains to be done. All that remains for you to do is to flesh out the subject in detail based on your own research work and that of others who are not able to be with us. I regret that Dr. Acra of Lebanon will not be able to attend. However, his work has been summarized and we have a copy of his full report for further study. Some of you may wish to read it. Unfortunately, this report is in draft form and cannot be distributed widely at this time.

IDRC's principal objective in sponsoring Workshops of this kind is to provide an opportunity for researchers along with selected implementers to review the state of the art in a defined subject area and identify outstanding research needs. It is expected that this will lead to the generation of new project ideas which could be developed into viable research proposals.

As an aid agency, you will find IDRC's modus operandi to be different than other aid agencies. Research projects supported by the Centre are identified, designed, conducted and managed by developing country researchers in their own countries to meet their own priorities. For more information, I would refer you to the IDRC brochure. Copies of the brochures, along with some typical publications which may be of interest to you, will be available for your perusal during the Workshop. If you wish to receive a copy of any of the publications, please add your name to the sign-up list.

IDRC's principal mandate is to assist developing countries in building indigenous research capacity/capability. Presently, there are seven research support Divisions in IDRC. These include Agriculture, Food and Nutrition Sciences, Social Sciences, Earth and Engineering Sciences, Information Sciences, Fellowships and Awards, Communications and Health Sciences. I represent the Health and Environment Program of the Health Sciences Division which deals principally with the "hard sciences". Dr. Donald Sharp, who will be with us on Wednesday, represents the Health and the Community Program of the Health Sciences Division which focuses on the socio-cultural-economic appropriate technologies. This aspect is very important. We may have the best and the most effective and appropriate technology available, but it may not be acceptable to the people on account of certain socio-cultural factors. It may also not be affordable to the poor.

The Centre's mandate is to assist developing country researchers to address problems related to the improvement of the quality of life of the rural and peri-urban poor. IDRC supports applied research and demonstration type projects which test different intervention strategies and compares them to conventional approaches. The focus is on the community. The objective is to assist communities in developing countries to improve their health status at a price they can afford. I don't need to tell you that this is a tremendous challenge.

The challenge for this Workshop, I believe, is to develop strategies/approaches on how best to introduce the solar disinfection technology to the poor in the Third World. This does not mean that there are still some important outstanding technical/scientific questions to be addressed and still to be resolved. These, I'm sure, will be highlighted during this Workshop and research proposals prepared. Nevertheless, I believe the time has come to test this technique under village conditions over an extended period of time to determine the socio-cultural-economic aspects and at the same time, test the effectiveness of this method of water disinfection under different climatic conditions. Am I jumping the gun? Have we arrived at a point where this can now be done? You may wish to debate this point during the Workshop.

I am confident that your deliberations will prove profitable. I trust you will exchange ideas both freely and frankly. I'm sure that I will be learning a good deal by sitting in and listening to the presentations and discussions. I noted that during the last day, time has been set aside for the "Development of Projects and Proposals for Further Research". From the IDRC side, Don Sharp and I will be available to discuss research ideas and IDRC procedures with you individually. Incidentally, such discussions do not have to be limited to that particular time slot. We will be available during lunch, coffee breaks and in the evenings to chat with you informally.

I wish you much success at this Workshop.

SUMMARY OF ACTIVITIES OF INRESA NETWORK ON SIMPLE SOLAR WATER DISINFECTION SYSTEM TESTING AND EVALUATION

Ron Alward

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INTEGRATED RURAL ENERGY SYSTEMS ASSOCIATION (INRESA)

INRESA is an association of individuals and organizations dedicated to improving the standard of living of rural populations in developing countries through promotion of effectively integrated renewable energy technologies. Begun at a United Nations University and Chinese Academy of Sciences sponsored Workshop in Guangzhou, China, in 1982, INRESA traces it's formation to a widespread frustration at the lack of examples of successfully operating renewable energy systems, despite the many efforts of Governments, local and international agencies to introduce these technologies. Today, the Association supports a network of close cooperation among members involved in field projects. The focus of activities is the development, demonstration and effective information dissemination on integrated rural energy systems, systems which exploit a community's human and renewable energy resources to meet the needs for food, water and productive output. Local conditions dictate technology orientation towards labour or energy intensiveness. The primary objective in the process of technology innovation or transfer is to motivate that necessary interaction between the technology and the individual and collective socio-economic and cultural influences.

Many renewable energy systems developed in industrialized countries are only economical when delivering large quantities of power. Energy systems typically developed and applied by INRESA members are adapted to meet more modest needs. Economies generally arise from the simplicity of the technologies and the supporting technical infrastructure, and from the generally more labour-intensive orientation of technology fabrication and use. Renewable energy technologies are often small in scale and are designed to meet locally urgent energy requirements.

INRESA PROJECT ON SOLAR WATER DISINFECTION

INRESA involvement on solar water disinfection dates back to the June 1985 INRESA meeting in Montréal. At that time a proposal was formulated at the INRESA Secretariat to extend and expand basic knowledge on a little known practical water disinfection technique, the exposure of small quantities of contaminated water to direct sunlight for a given period of time. Experiments by Acra and co-workers at the American University of Beirut, Lebanon, showed that exposure to sunlight can eradicate a variety of pathogenic bacteria. The purpose of the INRESA work would be to extend this knowledge by encouraging several other laboratories in different parts of the developing world to pursue this investigation and to lay the groundwork for information dissemination and technology transfer.

The rationale for this extension of Dr. Acra's work was that the disinfection process is potentially so simple and inexpensive that it deserved immediate independent corroboration prior to initiation of large scale technology transfer.

The Project, funded by the United Nations University was initiated as a Network Project in the sense that research was carried out at the Secretariat and at a number of research centres in developing areas of the world.

Initially, four developing area research institutions carried out the testing and evaluation:

- University of Piura, Peru	G. Baldi
- Los Gaviotas, Colombia	J. Zapp
- American University of Cairo, Egypt	S. Arafa
- Ceylon Electricity Board, Sri Lanka	B.P. Sepalage

A fifth institution was added during the final 18 months of the project:

- Obafemi Awolowo University, Nigeria	O. Odeyemi

Experimental procedures were developed at the outset of the project at the Secretariat in Montreal by O. Odeyemi and Brace Research Institute staff members.

OBJECTIVES

The immediate objectives of this project were to:

A) Verify the effects on the destruction of pathogenic bacteria caused by exposing contaminated water to sunlight.

B) Understand fully the mechanism under which this action takes place.

C) Determine the levels of solar radiation intensity and period of exposure necessary to eliminate a wide variety of pathogenic contaminants in water.

D) Encourage the repetition and field testing of this technology in a number of different countries so as to further expand the knowledge base and spread the practice of these techniques.

E) Determine the process necessary to diffuse information on this type of water purification system on a massive scale.

Initial work concentrated in five areas:

1) Repetition of Acra's work at each network centre.

2) Testing of the procedure on regionally endemic pathogenic bacteria.

3) Information gathering on suitable containers for solar water disinfection, particularly focusing on the physical and optical characteristics.

4) Establishing minimum threshold levels of solar radiation exposure.

5) Investigation of techniques to avoid re-contamination of stored disinfected water.

The activities of the centres in the INRESA Network are described in the following sections.

WORK AT BRACE RESEARCH INSTITUTE

1. As part of the cooperation between the INRESA Secretariat and the United Nations University, Dr. Olu Odeyemi of the Obafemi Awolowo University (Microbiology Department), spent the year following November 1985 at the Brace Research Institute. His principal activity was related to solar water disinfection. Dr. Odeyemi, a microbiologist, undertook the following activities:

   a) initiated a bibliography on solar water disinfection articles from the literature.

   b) networked with various members of the INRESA Secretariat on problems related to solar disinfection activities.

   c) interacted with Dr. Acra at the American University of Beirut in Lebanon on a variety of subjects related to the technique of solar water disinfection.

   d) produced a number of reports which served as background papers for the Network such as:

      i) U/86/24 -"Guidelines for the Study of Solar Disinfection of Drinking Waters in Developing Areas of the World"

      ii) U/86/32 -"The Use of Solar Radiation for Water Disinfection".

   e) established test facilities for solar water disinfection at the Brace Research Institute Experimental Station.

   f) ran a series of experiments to determine the effectiveness of the disinfection technique at locations remote from the Equator.

2. Linkage with the Smithsonian Institute: The disinfection project has many aspects requiring reference to specialists. Cooperation was freely obtained from researchers at the Smithsonian Institute in Washington D.C. with respect to specific wavelengths of solar radiation that may act in a germicidal fashion. Dr. Bernard Goldberg of their Environmental Research Centre supplied information relating to spectroscopic experiments isolating the portion(s) of the spectrum responsible for killing bacteria.

   Dr. Goldberg also recommended the use of controlled experiments with a dark control, that is, a sample of contaminated water which is not exposed to light for the duration of an experiment. This practice was used throughout the INRESA studies.

3. Linkage with the Institute of Parasitology and the Department of Microbiology of McGill University: All of the initial experiments on contaminated water were tested in the laboratories of the Institute of Parasitology and the Department of Microbiology.

4. Francis Dubé: Working at the INRESA Secretariat, Mr. Dubé ran a series of experiments to establish the effects of water temperature, container inclination and the use of reflectors on the solar water disinfection technique.

5. Joachim Hahn: Working on a WUSC Fellowship at Brace Research Institute, Sr. Hahn prepared an extensive annotated bibliography of more than 200 entries. In May, June and July 1988, he ran experiments to continue the earlier work of Odeyemi and Dubé. His work concentrated on determining the effect of angle of exposure of the container to the sun's rays, the effect of using river vs distilled water, the resistance of previously exposed bacteria to U.V. from the sun and the influence of turbidity and water temperature.

6. Dr. Tara Kandpal: Initiated a theoretical study of the physics of solar water disinfection.

ACTIVITIES IN EGYPT, PERU, COLOMBIA, SRI LANKA AND NIGERIA

Parallel to the above work at the Secretariat, the researchers in Colombia, Peru, Egypt and Sri Lanka embarked on their programmes. Generally, they directed efforts toward testing Acra's findings. As their projects developed, other objectives were addressed. Arafa and Cotis in Egypt looked at the characteristics of potable water and the bacteriology of naturally occurring waters in Egypt in terms of sources, types of pathogenic and non-pathogenic bacteria, water-borne diseases and naturally occurring purification processes. They tested 10 different transparent water containers available in Egypt and used contaminated water from various sources in Basaisa village, 100 km northeast of Cairo. Cotis did optical and ESR measurements of the various container materials and made extensive field surveys as part of her M.Sc. thesis programme.

In northern Peru, researchers studied local public water supplies for pathogenic micro-organisms, customs and habits as they relate to water collection, storage and use, and solar energy availability. In addition to testing solar decontamination of water in transparent containers, the researchers tested the germicidal effect of ultra-violet radiation entering from the top of open metallic, non-transparent containers. Such containers predominate throughout northern Peru.

Zapp and his team of researchers attempted to evaluate the effectiveness of Acra's water purification techniques in the cloudy, cool highlands of central Colombia. They studied waters with high human fecal contamination and others contaminated with hydrolyzed carbohydrates and proteins from the nearby coffee processing activities.

In Sri Lanka, researchers attempted to investigate the effects of container types, water temperature, turbidity and climatic factors on the disinfection process.

Upon his return to Nigeria in late 1986, Odeyemi undertook further experimental work in a tropical environment to both verify and extend Acra's findings. He assessed the influence of different shapes and colours of containers on the disinfection process,

investigated the effects of water turbidity and determined how isolated microbial and parasitic agents of water-borne diseases in Nigeria were affected by exposure to direct sunlight. Odeyemi also looked at the adverse effects of the rainy season on solar decontamination of water.

RESULTS

Findings at the INRESA Secretariat in Montreal, Canada

Complete decontamination of water samples was not achieved during many of the experiments because of weak and diffuse solar radiation during the period of study. The following results were significant:

a) Solar radiation seems to exert germicidal effects on coliform bacteria and also on total bacteria populations, with the former being more susceptible than the latter.

b) Bactericidal action of solar radiation may take only 3 hours on a clear sunny day, or several hours longer on a cold cloudy day.

c) Bacteria appeared to be more rapidly inactivated by solar radiation if the diluting medium was distilled water rather than stream or river water. Bacteria also appeared to be more susceptible to solar inactivation in autoclave-sterilized river water than in non-sterile water.

d) Sewage water may not be completely disinfectable by solar radiation.

e) Individual pure cultures of bacteria such as E. coli. S. typhi, S.aureus and S.flexneri appear to be more readily inactivated by solar radiation than the mixed cultures of organisms.

f) The period of most rapid decline in bacteria population also coincides with the hours of high insolation (10:00 to 13:00) in most of the cases.

g) It is possible to achieve a complete decontamination of a fairly clarified water without any danger of bacterial regrowth, if the disinfected water is properly stored.

h) An improperly disinfected water may result in substantial increase in bacterial density during overnight storage.

i) Results show that the vertical or horizontal positioning of water bottles exerts no influence on the rate of solar destruction of bacteria.

j) Solar radiation rather than temperature may also play some role in the demise of bacteria in water samples exposed to sunshine.

k) The Swab and Count technique appears to be a reasonably suitable method of assessing solar disinfection of polluted water mainly because of its rapidity and also because of its ease of use, simplicity, time and labour saving. The method seems to be more suitable for evaluating coliform bacteria, the indicators of

fecal pollution of water, than for enumerating total bacteria, if their concentration is higher than 500/ml.

l) The investigation of exposure of the protozoan parasites to solar radiation was not conclusive, nevertheless it appears that the cysts of Giardia muris. may be susceptible to solar inactivation.

Findings in Egypt

Experimental work dealt mainly with monitoring total bacteria in contaminated water supplies, with less emphasis on fecal indicator bacteria. In this context, the following results were achieved:

i) The fieldwork in Basaisa was limited to sampling and bacteriological testing of water collected from various sources in the village, as well as identifi- cation of the kinds of containers used by the villagers for water storage.

Sixteen water sources in the Village of Basaisa were examined to determine their bacteriological load. The most contaminated stream had 10^7 bacteria/ml while the most contaminated wells contained in excess of 4×10^5 bacteria/ml. These sources were used for the investigation on solar disinfection of water. In experiments, researchers recorded a 99.9% decrease in total bacteria within 3 hours of exposure to intense pre-noon sunlight.

ii) In other experiments, the rate of decline of total bacteria was found to be highest in transparent glass containers followed by blue containers, green containers and brown containers in that order. Water temperatures typically rose from 20°C to about 41°C between 08:30 and 13:30 hours, during which time the total bacteria declined to 0.1% of their original value.

iii) Transmissivity measurements indicated that the best wavelength range for light transmission through glass and clear plastic is 4000-5000 A°.

iv) The project confirmed the results of Dr. Acra et al., under the conditions prevailing in Cairo. Sunlight (particularly the near-U.V. component) appears to be effective in destroying bacteria present in contaminated water. Initial bacterial populations were typically very high. The result was that relatively high exposure times were required to destroy 99.9% of the initial bacterial population.

v) It was found that, in practice, the shape of the container has little effect and can be overlooked. However, volume of containers has some effect. The larger the volume the quicker the kill rate (volumes studied 100 ml 500 ml). (There could be a threshold effect here).

vi) Temperature has little effect within the ranges studied. One experiment with coloured bottles (brown and turquoise) showed that the temperature increased in each bottle, but there was a higher kill rate in the turquoise coloured bottle.

vii) During cloudy days, it is found necessary to prolong exposure to sun.

Findings in Peru

The climate in Piura, northern Peru, is arid and hot. The sun shines virtually every day of the year. Researchers here found that:

i) Only 5 10% of the rural population in northern Peru obtained their water from publicly maintained water sources. The vast majority of people get their drinking water from rivers, canals, surface wells and deep wells. These water supplies are typically very contaminated and the methods of collecting, transporting and storing the water adds to the contamination. Analysis shows public supply water to have up to 350 coliform/ml and natural sources up to 1600 coliform/ml. The contamination level of water sources varies due to the seasons of the year and the presence of domestic animals.

ii) Water related diseases are the primary cause of sickness among the total population and the second cause of death among children in northern Peru. The principal pathogenic agents are E.Coli, Salmonella typhosa, S.paratyphi, Shigella disenteriae and Enterovirus.

iii) Daily solar radiation intensities in northern Peru are very suited to solar disinfection of contaminated water. There is an average of only two days per year with less than 1.5 kW-h/m^2-day intensity in Piura, the minimum dose for killing Salmonella spp.

iv) Transparent glass or plastic bottles are not readily available in northern Peru. Open-top 20 litre metal pails and 10 to 30 litre plastic drums are typical.

v) All coliform bacteria in water intentionally contaminated with urban sewage and placed in transparent bottles can readily be eliminated upon exposure to 2 hours or more of good sunlight. Water in the plastic drums or in the open-top metal pails can be de-contaminated in 2 1/2 to 3 hours.

vi) Total bacteria can rarely be eliminated upon exposure to the sun. In artificially contaminated water 90% of total bacteria can be eliminated in less than 4 hours exposure to sunlight. However, if allowed to sit overnight, their number can increase to as much as 10 times the original concentration.

vii) Coliform bacteria from water with frequent exposure to the sun appear to be more difficult to kill.

viii) Solar radiation has less effect on total bacteria in contaminated water normally exposed to the sun, than it does on the bacteria in contaminated water from deep wells, subterranean streams and turbid rivers.

ix) Increase in temperature of the contaminated water (above 36°C appear to affect the decontamination rate. This effect has to be confirmed by further experimentation.

Findings in Colombia

The climate in the mountainous area of Colombia where these experiments took place is characterized by dense cloud cover. Solar radiation intensities are among the lowest in

the world at the site latitude. The region has high population density with inefficient disposal of human excreta. In addition, waters are continuously contaminated with hydrolyzed proteins and carbohydrates from the washing of coffee beans. The result is a high index of waterborne diseases. Experimental work under this project determined that:

i) There is a general tendency of solar radiation to reduce total bacteria, total coliform and fecal coliform counts.

ii) In only a very few tests were bacteria reduced to acceptable clean water standards. These coincided with days of high direct solar radiation.

iii) There is a definite lower limit for use of this method of water purification. This lower limit is not clear. However, it would appear that use of the technology is severely restricted in areas or seasons with significant cloud cover.

iv) A portable incubator, for the water samples, was developed as part of the fieldwork.

Findings in Sri Lanka

No significant findings resulted from the experimental work in Sri Lanka. Project results show, perhaps, the need for rigorous adherence to good scientific practice when undertaking an experimental programme of this nature. Procedures used which caused problems were:

- storage of water samples without sterilization of equipment
- residuals of lactose and other nutrients in test samples of water due to method of introducing bacterial contaminants.
- inconsistent initial bacteria counts in experimental and control samples.

Findings in Nigeria

i) Water related diseases are common and sometimes endemic in rural and suburban areas of Nigeria where people have little or no access to treated water supplies. Relatively high morbidity and fatality rates are associated with these diseases.

ii) Solar radiation can be used to disinfect drinking water. Exposure of bacterially contaminated stream and well water samples to intense solar radiation of at least 600 W/m^2 for 5 hours can render the water safe to drink.

iii) The rate of solar inactivation of coliform bacteria was faster than solar inactivation of the total bacteria population of contaminated water samples. Total inactivation of total bacteria was never achieved. However all coliforms were eliminated, typically after 5 hours exposure to intense sunlight.

iv) V.cholerae and S.aureus were rapidly and completely inactivated upon exposure of their water cultures to high solar intensity.

v) Sewage-laden stream water may not be completely disinfected by solar radiation due to the presence of nutritive elements which encourage microbial proliferation.

vi) Very turbid waters are not easily decontaminated by sunlight.

vii) Clear transparent containers are more effective than green coloured bottles.

viii) Solar inactivation of pathogenic and non-pathogenic bacteria cannot be achieved during days of heavy cloud cover.

ix) Mean solar intensities are highest from 10:00 hours to 16:00 hours on sunny days. Exposure of contaminated water to the sun should preferably be carried out during these hours to achieve a reliable degree of decontamination.

SUMMARY OF PRINCIPAL FINDINGS

Experimental work was carried out in 6 locations across the world. Results from all the programmes tend to confirm the findings of Acra and co-workers, that solar radiation has a bactericidal effect on bacterially contaminated water. In four of the locations, results consistently revealed that E.coli can be totally eliminated and the total bacteria count considerably reduced, upon exposure of contaminated water in transparent containers to solar radiation. In the two remaining projects, although the general trend towards less total bacteria and E.coli was evident, experimental procedures and/or climatic factors did not permit complete elimination of pathogenic bacteria.

Complete elimination of pathogenic bacteria requires a minimum of 2 hours exposure to direct solar radiation of $600W/m^2$ intensity. The recommended exposure time to provide a safety factor for humid tropical regions is 5 hours exposure, centered around solar noon.

Relevant climatic conditions relate only to the availability of direct solar radiation. Partly cloudy periods during exposure are acceptable so long as the average solar intensity is in excess of $600W/m^2$ over the exposure period. Heavy cloud cover, or, potentially, any other conditions which occlude the sky such as heavy dust or smoke, render the disinfection process less effective.

The general consensus from the tests in 6 locations is that the increase in temperature of the contaminated water, due to exposure to the sun, has very little effect on the rate of decontamination. The maximum water temperature recorded in the tests was 42.8°C, which is below the thermal death points of most bacteria.

Other pathogenic bacteria in addition to E.coli can be easily eliminated by this process. V.cholerae and S.aureus were both completely inactivated after 5 hours of exposure to direct sunlight in Nigeria.

Highly contaminated waters, such as sewage wastes, are not easily disinfectable by solar radiation. Neither are highly turbid waters, such as in some rivers. It is likely that turbidity has an attenuating effect on the solar radiation and that nutritive elements in the sewage wastes encourage some microbial proliferation.

Experiments done using distilled or sterilized water as the dissolving medium showed more rapid inactivation of bacteria upon exposure to the sun than was evident when using untreated natural water. The most likely contributing factor is the lack of sustaining nutrients in distilled and sterilized waters.

One research team found it more difficult to inactivate pathogenic bacteria from waters normally exposed to the sun, than from underground and deep well waters which rarely or never see the sun. A potential reason is the possible acquired tolerance to U.V. radiation of the surface water bacteria.

The shape and size of containers in which to expose contaminated water to the sun appeared to have little effect on the decontamination rate. The Egyptian experience, however, showed a tendency to quicker bacteria kill rates in 500 ml containers than in 100 ml containers. Both of these container sizes are much smaller than typical water collection and storage containers in common use throughout the developing world. Horizontal or vertical positioning of these containers also had little effect.

The colour of the transparent containers, on the other hand, is an important consideration. Whether the container be glass or plastic, the preferred colour is colourless. Light violet or light blue are also acceptable. Brown, green, yellow and red transparent containers should not be used.

The highest degree of decontamination is obtained in containers transmitting in the near U.V. region of the light spectrum. The most lethal range for germicidal effect is in the near U.V. up to 500 nm.

Metallic containers with open tops and reflective interior side walls can also be used effectively for solar decontamination of water. However, exposure time has to be increased by 1 to 2 hours.

The experimental programme focused on testing the effect of solar radiation exposure on certain pathogenic bacteria of exposing contaminated water to sunlight. The general consensus is that solar radiation can be effectively used to decontaminate water and render it safe to drink. Also, there is now a better understanding of the lower limits of exposure time and solar intensity required to eliminate E-coli and a few other pathogenic bacteria. Minimum exposure time varies from 2 hours in hot-arid areas, to 4 to 5 hours in humid tropical regions or when the sun is partly obscured by clouds. More research is necessary to determine if other water related pathogens are susceptible to solar inactivation.

However, we do not yet fully understand the mechanism under which this decontamination takes place. It seems evident, from limited experimental results, that the bactericidal effect is accounted for by the wavelength of the incoming light and that the most lethal range of the light spectrum is in the near U.V. up to about 500 nm. However, that lethal range has not been precisely identified, nor do we know if that is the only lethal range although clearly, it is the most effective. The effect of temperature has been shown to be negligible in the range of temperatures monitored. The combined effects of somewhat higher water temperatures and U.V. radiation of lower intensities (for example during cloudy periods) may have significant bactericidal effects. There is also the unknown factor of how the bacteria are actually inactivated by the U.V. radiation. A better understanding of this mechanism may provide useful information for larger scale water purification.

The fourth objective, to encourage field testing in a number of different countries, has been built into the organization of this project, wherein experimental work was carried out in 6 different countries. Two additional country projects have been initiated as a result of the INRESA project one in Ghana and another in Thailand.

Enough information and data are available now to assess where future activities should be concentrated and to allow us to look towards mechanisms of diffusing this information. The underlying aim of this project was to make a very simple technology for water decontamination available to the masses of people throughout the world who have no clean water supply. What has been discovered to date is important enough and consistent enough for us to begin to look at this process of information dissemination.

It is evident that a considerable amount of additional research is necessary in order to extend these preliminary findings, so that the technology can be utilized effectively under field conditions.

FUTURE ACTIVITIES

Solar Water Purification Activities in Ghana

During the summer of 1987, Abeeku Brew-Hammond, of the University of Science and Technology, Kumasi, Ghana, undertook a stage at the Brace Research Institute. He was the recipient of a Mini-Research Project Grant from the United Nations University, under the auspices of INRESA. While his activities at the Brace Research Institute concentrated on related work being undertaken with IDRC, Ottawa, he was nonetheless able to assimilate similar fields of interest which could make an impact in his home institution.

On his return to Ghana, he encouraged Prof. Oldham, Head of the Biochemistry Department of the University of Science and Technology to take an interest in solar water purification techniques.

In May 1988, T.A. Lawand visited the University of Science and Technology and was able to help initiate a project on solar water purification techniques. Two Danish engineering volunteers -Marie Anne Laurtzen and Charlotte Andersen had been studying this field and were about to begin a series of experiments. They are supervised by Mrs. A. Asaré (of the Civil Engineering Department) who had recently completed graduate studies in Environmental Sanitation. They are currently undertaking tests, utilizing the facilities and equipment of Prof. Brew Hammond's Solar Energy Laboratory in Mechanical Engineering an excellent example of inter-disciplinary research.

Wherever this technique is discussed in developing areas and positive elements are present, it is noteworthy that this technique is readily adopted as a research theme.

Solar Water Purification Activities at Khon Kaen University, Thailand

A solar water purification project is being initiated in Northeast Thailand under a CIDA sponsored institutional linkage programme between McGill University and Khon Kaen University.

The project fits in the general theme of the linkage programme, that is, the development of local expertise in the field of renewable energy research, development and dissemination. At the same time it is a highly relevant study area with the Thai Government's major development programme on "Greening of the Northeast".

A water purification project is a natural follow-on of earlier rainwater catchment programmes which have had a major impact on provision of drinking water to virtually every rural community in Thailand. Recent studies have indicated however, that the collected rainwater is not free of bacteriological contamination. In fact, very few test samples in a recent survey met WHO safe drinking water standards for total bacteria, Coliform or E.coli counts.

Prof. Wanpen Wirojanagug, an Environmental Engineer with the Faculty of Engineering, and Dr. Sastri Saowakantha, a Microbiologist, and Vice Rector for Research Affairs at Khon Kaen University, will be the principal researchers, with assistance from lab technicians and graduate students. Generally, the objectives of the study are similar to those of the now completed Mini Research Projects. Dr. Acra's experimental findings from Beirut will be tested and evaluated under Northeastern Thailand conditions. Studies will be made of water-borne diseases and microbial and parasitic agents frequently found in Thailand and procedures will be developed for simple solar disinfection of water, suitable for use with the isolated rain water catchment systems on individual houses.

RECOMMENDATIONS FOR FUTURE RESEARCH RESULTING FROM INRESA PROJECT

During the course of the INRESA network project a number of recommendations have been made for future research. The initial grants to each individual researcher were very small due to scarce research funds. It is however interesting to note that new activities are coming up and that some of the original starters are continuing. The activities undertaken to date on this project are only the beginning of what is no doubt a very large field of scientific work. It would be useful to consider extending these activities for the benefit of the global community. The basic recommendations then are as follows:

A) Seed money should be provided to encourage organizations undertaking research in developing areas to help initiate or continue their activities.

B) Standardization of testing methods for bacterial contaminants should be undertaken so that results are reasonably inter comparable.

C) The shape and size of container for testing purposes should be standardized at least for the laboratory phase in the development of this technology.

D) Specialized laboratories should be utilized to help determine the specific spectral germicidal effects, given the necessity for specialized complex equipment for measuring purposes.

E) Once the specific wavelengths have been identified it might be possible to examine with the glass or plastics industry the possibility of manufacturing a long lived container with stable solar radiation transmission properties which has a high rate of transmission for these wavelengths.

F) Experiments should be undertaken to determine the optimum shape of open containers, avoiding all possibility of further contamination during the exposure period and possible recontamination during the transfer of the water to another vessel within the consumer's residence.

APPENDIX 1. PERSONS AND INSTITUTIONS PARTICIPATING IN THE INRESA RESEARCH NETWORK ON SOLAR WATER PURIFICATION

(for personal addresses and telephone numbers, please refer to the Annotated Bibliography at the end of this document)

1. INRESA SECRETARIAT - Brace Research Institute, Canada
- T.A. Lawand (Engineer)
- R. Alward (Engineer)
- J. Hahn (Biologist, Universidad del Norte, Colombia)
- F. Dubé (Engineer)

2. Centro Los Gaviotas, Colombia
- Jorge Zapp (Engineer)

3. Technical University of Pereira, Colombia
- Jorge Santacruz (Microbiologist)
- José Moncayo (Microbiologist)
- Martha Montes (Laboratory Technician)
- Napoléon Hernandez (Biophysicist)

4. American University in Cairo, Egypt
- S. Arafa, Physics Dept (Physicist)
- I. Reda (Microbiologist)
- M.C. Cotis (Engineer)
- B. Abulnaga (Engineer)

5. Obafemi Awolowo University, Ile-Ife, Nigeria
- O. Odeyemi, (Microbiologist)

6. Universidad de Piura Piura, Peru
- G. Baldi (Engineer)

7. Centro de Salubridad de Tratamiento E Investigacion (CESAPTI)
Piura, Peru
- Maria del Rosario Fiestas Chunga (Microbiologist)

8. Ceylon Electricity Board, Colombo, Sri Lanka
- B.P. Sepalage (Engineer)

9. Ceylon Institute of Scientific and Industrial Research, Colombo, Sri Lanka
- Janaki Gunaratne
- Sirima Abangama
- S.A.Abeysekara
- G.S. Jayatilake

10. Khon Kaen University, Thailand
- Sastri Saowakantha (Vice-Rector for Research Affairs)
- Wanpen Wirojanagug (Environmental Engineer)

11. University of Science and Technology, Kumasi, Ghana
- J. Oldham (Biochemist)
- A. Asaré (Microbiologist)
- A. Brew-Hammond (Engineer)

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PROSPECTS AND LIMITATIONS OF USING SOLAR ENERGY FOR WATER DISINFECTION

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ABSTRACT

Roughly 75% of rural populations do not have access to treated water supplies. According to the WHO, 80% of all diseases are attributable to unsafe water and consequently about 1 1/4 billion people in the world are suffering from the major water-related diseases at any one time. The International Drinking Water Supply and Sanitation Decade (1981-1990) was launched by the UN to promote safe water and adequate sanitation for all. One of the simplest and least costly possible means of providing safe drinking water in villages is the use of solar radiation for disinfecting bacteriologically contaminated water. This technique consists of merely exposing the contaminated water to sunshine. To achieve effective disinfection, the water must be non-turbid and exposed in a transparent container to at least 600 W/m^2 of instantaneous sunshine for about 5 hours. In addition, the water must preferably be small in volume and be relatively low in bacteria content. However, solar decontamination may not be feasible if the water is heavily contaminated e.g. with sewage or if it contains solar resistant bacteria. Similarly, rainy seasons may mitigate against the effectiveness of the technique.

Several questions are posed to highlight the paucity of data and stress the need for further research.

INTRODUCTION

About 75% of rural populations do not have access to treated water supplies (Lewis, 1985). Such rural dwellers depend mainly on untreated stream, pond and well water for drinking, food preparation and other domestic activities. Unfortunately, sometimes these water sources are also the repositories of household wastes, animal manure, human faeces and community waste water as stream or river dumping is a major means of waste disposal (Odeyemi, 1987). For instance, in the River Niger Delta area of Nigeria, the water-locked inhabitants discharge their rectal wastes directly into waterways which they also use for bathing, laundry and drinking (Akinluyi and Odeyemi, 1984). In some villages or farms it is not uncommon to find barnyard, pigsty, chicken coop, privy and cesspool in close proximity to the stream or open well that supplies drinking water. Hence, drinking water sources are usually faecally polluted (Okoronkwo and Odeyemi, 1984; Petters and Odeyemi, 1985) and consequently water-borne diseases such as cholera, typhoid fever, dysentery, poliomyelitis and giardiasis are common occurrences in such rural communities (Odeyemi and Babalola, 1984 and Odeyemi 1986a).

The magnitude of health problems posed by the inadequate quality and quantity of water can be estimated by assessing casualties due to water-related diseases. For instance,

the World Health Organization (WHO) has estimated (Bourne, 1982) that, worldwide, 80% of all disease is attributable to unsafe water and at any time, one half the hospital beds in the world are occupied by people with water-related diseases. According to WHO, estimates of the number of people suffering from the major water-related diseases at any one time is about one and a quarter billion (Agarwal et al., 1981). There are one billion cases of diarrhoea every year in the developing areas of the world, causing 25 million deaths, which include 16,000 infant deaths every day.

Apart from the killer diseases like diarrhoea, cholera and typhoid, other water-related diseases such as dracunculiasis (Guinea worm), ascariasis (round worm) and schistosomiasis (bilharzia), exercise considerable debilitating and incapacitating effects to take their toll on human health (Lewis, 1985). For instance, it has been estimated that one quarter of Nigeria's working population between 15 and 40 years of age may be incapacitated by Guinea worm for at least 10 weeks each year.

The International Drinking Water Supply and Sanitation Decade (1981 1990) was launched by the United Nations in November 1980, to highlight the need for provision of adequate and safe water for all. However, to achieve this target, it has been calculated that, throughout the period, some 500,000 people will need to be given new or improved water installations every single day for the duration of the Decade, with an annual expenditure of US $30 billion (Lewis, 1985). Therefore, the reported feasibility of using solar energy to disinfect bacterially contaminated water at no or extremely low cost should hold promise for substantially reducing the estimated colossal costs of achieving the aims of the Water Decade.

Preliminary reports from Lebanon (Acra et al., 1984), Egypt (Cotis, 1986), Peru (Baldi, 1986), Canada (Odeyemi, 1986b) and Nigeria (Odeyemi, 1987) have indicated the possibility of using solar energy to disinfect bacteriologically contaminated water. Therefore, what are the prospects and limitations of employing sunshine for rendering unsafe water potable?

METHODOLOGY OF ASSESSING SOLAR DISINFECTION OF WATER

In most of the investigations carried out so far the assessment of solar decontamination of water involves exposing one to two litres of water samples in transparent containers to solar radiation for some hours and determining the changes in the bacteriological integrity of the water (Acra et al., 1984; Cotis, 1986; Baldi, 1986; Odeyemi, 1986b and Odeyemi, 1987). Control samples are usually kept in complete darkness. It must be noted that the efficacy and efficiency of this seemingly simple technique of water disinfection depend on several factors, some of which are enumerated below:

(a) the type and characteristics of the containers e.g. colour, shape, size, wall thickness and transparency to sunlight,

(b) clarity of the water (i.e. degree of turbidity) and water volume and depth,

(c) the intensity of sunlight at the time of exposure, which in turn depends on geographic location (i.e.latitude), seasonal variations, cloud cover, effective range of wavelengths of light, and time of the day,

(d) the kind of bacteria being exposed, the nature and composition of the medium, and the presence of bacterial growth supporting nutrients (Acra et al., 1984, Odeyemi, 1986a and Odeyemi, 1986b).

(e) length of time of water exposure to sunlight.

The methodology of total bacteria enumeration may be by membrane filtration technique, dilution and plating method or Swab and Count procedure, using nutrient agar as the growth medium (Odeyemi, 1986b). However, in case of coliform bacteria whose presence in water is used as an indicator of faecal pollution, special culture media such as MacConkey medium, Lauryl tryptose broth, brilliant green lactose bile broth and eosin methylene blue agar are employed for enumeration (APHA, 1981). Specific agents of water-borne diseases such as Salmonella, Shigella, Vibrio cholerae and Giardia lamblia also require specialized methods and selective media for estimation, isolation and identification.

When necessary, experiments are designed to investigate any of the aforementioned factors that influence solar decontamination of water. For instance, samples of contaminated water may be exposed to sunshine in transparent versus opaque containers, coloured versus colourless bottles, thick versus thin walled containers or horizontally versus vertically positioned bottles.

PROSPECTS OF EMPLOYING SUNSHINE FOR WATER DISINFECTION

Based on our investigations, so far, it seems reasonably well established that the rays of the sun may effect bacteriological disinfection of water if the following conditions are met:

(a) Non-turbid Clear Water Exposed to Sunshine in Transparent Containers:

It has been shown that bacteria are more rapidly inactivated by solar radiation in clear nonturbid water than in turbid water (Odeyemi, 1986b and Odeyemi, 1987).

As can be observed in Table 1, the coliform content of distilled water exposed to sunshine disappeared completely within 4 hours of exposure. On the other hand, the coliform level of a turbid sewage contaminated pond (see Table 2) was only slightly reduced from $3x10^3$ml to $1x10^3$/ml after 4 hours of exposure (Odeyemi, 1987). Similarly the total bacteria content of distilled water suffered substantial reduction in population during exposure to sunshine. It should be noted that even the bacteria content of distilled water kept in the dark petered out and eventually died out probably due to lack or dearth of growth supporting nutrients in the distilled water.

The practical implication of the above observation is that village water resources and sources such as rain, spring, well and stream that are relatively clear and nonturbid can be readily disinfected by exposure to sunshine in transparent containers.

In fact, such water samples may even be rendered completely sterile by solar energy thus making them ideal for practical applications such as preparation of oral rehydration solutions, mixing of infant food formula and dressing of wounds at village clinics. In view of the rapid disappearance of bacteria in distilled water, it is

suggested that researchers do not use distilled water for making up their test samples for solar water disinfection investigations.

(b) Water with Low Bacterial Load:

Generally, the lower the bacterial density of nonturbid water, the faster the rate of solar decontamination of such water. For instance, the total bacterial population of a stream water sample was reduced from 8.2×10^5/ml to 4.2×10^2/ml (i.e. 99.85% reduction) during 4 hours of exposure to the rays of the sun. On the other hand, the bacterial load of a more heavily contaminated stream water was only slightly reduced from 4.5×10^6/ml to 1.8×10^6/ml (i.e. 60% reduction) during the same period of sun exposure (Odeyemi, 1987). The reason might be due to easier penetration and inactivation of scattered individual bacterial cells by the sun's rays in low density water, than in the cluster of cells in the high bacterial density water. However, low density water sources harbouring solar-resistant strains of bacteria may not be readily disinfectable (Baldi, 1986).

It should also be noted that individual pure cultures of bacteria such as Escherichia coli, Salmonella typhi, Staphylococcus aureus, Shigella flexneri and Vibrio cholerae are more readily inactivated by solar radiation than the mixed cultures of organisms. Similarly, bacteria are more susceptible to solar inactivation in sterile than in non-sterile stream samples and coliform bacteria are more susceptible to solar inactivation than total bacteria (Odeyemi, 1986b and Odeyemi, 1987).

(c) Relatively Small Volume of Exposed Water:

Though the exact penetrable depth of water by the sun's rays to inactivate bacteria is not known, it is reasonable to assume that a relatively small volume of clear water would be more readily penetrated and decontaminated than a bulky volume of water. For instance, it has been reported that distilled water will absorb 8% of the applied UV energy at a depth of 3 cm and reflect about 2% at the surface, transmitting the rest (Weber, 1972). In spite of the operational inconvenience a housewife may experience in carrying out the solar disinfection procedure on small batches of water everyday, the small volumes of water should be more reliably disinfected than large volumes (Acra et al. 1984; Odeyemi, 1986a).

Solar decontamination operations should be performed during periods of high insolation such as from 10:00 to 16:00 hours on a sunny day. According to Odeyemi (1987), exposure of clean stream or well water samples to intense solar radiation of at least 600 W/m^2 for 5 hours can render a bacteriologically contaminated water safe to drink.

LIMITATIONS OF THE SOLAR WATER DISINFECTION TECHNIQUE

Despite the apparent simplicity of the solar water disinfection phenomenon there are certain factors that may mitigate against the effectiveness of the process. Some of such factors are discussed briefly below.

(a) Sewage and Sewage Contaminated Water, Turbid Water:

Sewage or sewage-laden pond water may not be completely disinfectable by solar radiation (Table 2) because of its high turbidity which can exert attenuating effects

on the transmission of the rays of the sun, and also due to the presence of nutritive elements in the sullage which can encourage microbial proliferation (Odeyemi, 1986b).

For similar reasons a highly turbid water may not be safely disinfectable. Therefore, in order to reduce the physical, chemical and microbial loads of a turbid water to facilitate the disinfection process the water must be clarified prior to exposure to sunshine (Odeyemi, 1986a). Otherwise, a greater intensity of solar radiation and/or a much longer time of exposure may be needed to achieve decontamination of a heavily contaminated water sample.

(b) Solar-Resistant Bacteria:

It seems that some strains of autochthonous bacteria may acquire solar-resistance especially in water sources that are permanently or continuously exposed to sunshine.

Though conclusive, temperature was recorded with a Celsius scale mercury thermometer, while solar radiation was measured with a mechanical Pyranograph, model 3010. scientific evidence for this hypothesis is yet to emerge. Baldi (1986) in Peru, speculated that the ineffectiveness of solar energy as a water disinfectant was due to the over-exposure of the water source to the sun's rays, which presumably have selected the bacteria content for solar resistance. It however seems highly improbable that autochthonous organisms such as the etiologic agents of water-borne diseases would develop solar resistance since they are only occasionally introduced into waterways. Nevertheless it is necessary to ascertain the innocuousness of any solar resistant strains of bacteria in water sources having this problem.

(c) Rainy Seasons:

Solar disinfection of bacteriologically contaminated water may not be feasible during days of continuous heavy downpour as witnessed during the rainy seasons in the tropical World (Odeyemi, 1987). As seen in Table 3, the extremely weak, diffuse and attenuated solar radiation that filtered through a heavy cloud cover on a rainy day failed to effect any noticeable decrease in either the total bacteria or the coliform content of the stream sample. The rainy season may pose a serious threat to the successful implementation of the solar disinfection technique especially when it is realized that water sources are more prone to contamination by run-off, erosion and leaching during the rainy season than during the dry season. It should be noted that the periods of the rainy seasons differ from one tropical country to another. For instance, in Malawi, the rainy season is from December to April and the dry season is from May to November, whereas in Nigeria, December to April is the dry season while May to November is the rainy season.

CONCLUSION

Owing to paucity of scientific data it is not possible to make conclusive statements on the overall reliability and practicability of the solar water disinfection technique. There are still many questions unasked or unanswered. For instance, what is the recipe for preventing water recontamination? Is there a rapid technique of ascertaining water decontamination especially at village level? How effective are traditionally used and locally available water containers in transmitting light to disinfect water? What are the suggestions for disinfecting water during the rainy seasons? Does high temperature

play any role in the solar-kill of bacteria? Is solar resistance a serious problem? What are the exact mechanisms of solar inactivation of bacteria? Is it quite practicable or cost-effective to use solar concentrators for enhancing solar decontamination? Will sunshine inactivate the non-bacterial biotic contaminants of drinking water such as viruses, protozoa and helminths? For example, virus contamination of sewage was studied in Ottawa by Sattar and Westwood (1977) who found that 79% of sewage samples examined contained human pathogenic viruses. Rao et al. (1978) in India also found that nearly 80% of the viruses in sewage were poliviruses. It has been suggested (Agarwal et al., 1981) that one third of the world's population is infected with one or more species of nematodes, roundworm, hookworms or whipworms. What is the remedy for decontaminating water containing nonbiotic contaminants such as fertilizers, pesticides, acid mine drainage, radioactive substances and industrial chemicals? Will this method of water treatment be socio-culturally acceptable, bearing in mind that local taboos, voodooistic beliefs and superstitions exist in many peasant communities?

The array of questions posed above obviously point to the need for further research in the use of solar energy for water disinfection. It is also important to organize training and demonstration courses for villagers, rural extension workers and public health technologists in order to spread the technology. In this regard it will be useful to establish regional research and training centres in selected areas of the developing world. The year 1990 will mark the end of the Water Decade but by no means the end of the search for techniques of providing safe drinking water for rural populations.

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TABLE 1 EFFECT OF SOLAR RADIATION ON THE COLIFORM AND TOTAL BACTERIA DENSITY OF 500 ml OF CONTAMINATED DISTILLED WATER IN 750 ml TRANSPARENT GLASS BOTTLES (Odeyemi, 1986b).

Sample type	Hours of exposure				
	0	4	20	24	30
SI = sample exposed to sunshine					
Total bacteria/ml	$6x10^4$	$5x10^3$	$6x10^2$	0	0
Coliforms/ml	$5x10^2$	0	0	0	0
DI = sample placed in darkness					
Total bacteria/ml	$2x10^4$	$9x10^3$	$8x10^3$	$6x10^3$	0
Coliforms/ml	$9x10^2$	$6x10^2$	$5x10^2$	0	0

NOTE: SI experienced weak insolation and overnight darkness between 6 and 24 hours of exposure.

TABLE 2 INFLUENCE OF SOLAR RADIATION ON THE TOTAL AND COLIFORM BACTERIAL DENSITY OF 500 ml SAMPLES OF A SEWAGE-CONTAMINATED POND EXPOSED TO SUNSHINE IN 500 ml TRANSPARENT BOTTLES (Odeyemi, 1987).

Sample type	Hours of exposure			
	0	2	4	6
Sample A exposed to sunshine				
Total bacteria/ml	4.5×10^6	8.6×10^6	1.8×10^6	1.4×10^6
Coliform bacteria/ml	3×10^3	4.6×10^3	1.1×10^3	4.6×10^2
Water temp.,°C	30	35	38	36
Solar intensity,W/m^2	539	613	697	262
Sample B incubated in the dark				
Total bacteria/ml	1.1×10^6	2.8×10^6	1.8×10^6	1×10^6
Coliform bacteria/ml	2.8×10^3	3.5×10^3	1.1×10^3	4.2×10^3
Water temp.,°C	30	32	33	32

TABLE 3 EFFECT OF A RAINY DAY ON SOLAR DISINFECTION OF 500 ml OF STREAM WATER CONTAINED IN 500 ml TRANSPARENT BOTTLES, KEPT OUTSIDE ON A RAINY DAY (Odeyemi 1987).

Sample type	Hours of exposure/incubation			
	0	2	4	6
Sample A, exposed to daylight in the rain				
Total bacteria/ml	$7x10^5$	$6.8x10^5$	$6.4x10^5$	$5.3x10^4$
Coliform bacteria/ml	$3.1x10^2$	$3x10^2$	$2.8x10^2$	$1.3x10^2$
Water temp., °C	28	30	29	29
Solar Intensity, W/m^2	177	209	281	257
Sample B, kept in a dark cupboard				
Total bacteria/ml	$7.2x10^5$	$8.3x10^5$	$6.9x10^5$	$5.8x10^4$
Coliform bacteria/ml	$2.9x10^2$	$3x10^2$	$2.7x10^2$	$1.2x10^2$
Water Temp.,°C	28	29	30	29

NOTE: Temperature was recorded with a Celsius scale mercury thermometer.
Solar radiation was measured with a mechanical Pyranograph, model 3010.

SOLAR WATER DISINFECTION IN PERU

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ABSTRACT

The environmental conditions and the reliability of solar water disinfection have been studied in the northern coastal region of Peru. Poor economic conditions, lack of public water systems, heavily contaminated drinking water sources have made it urgent to provide simple disinfection systems to the population. Solar radiation is favorable to solar water disinfection. The germicidal effect of the sunlight have been demonstrated into a variety of containers and test conditions.

INTRODUCTION

The availability of drinking water is an essential feature for preventing endemic diseases and improving the quality of the life. Most rural villages in developing countries have poor access to clean water. The diffusion of current methods of water disinfection, like chlorination or boiling, is prevented by their serious limitations: change of the water flavor, high cost and low availability.

The purification effect of the sun is empirical ancestral knowledge. The germicidal effect of the light was demonstrated scientifically by Downes and Blunt [1] in 1877 and it is currently applied in many fields [2]. In 1984, an extensive experimental work was carried out at the American University of Beirut on behalf of UNICEF. Promising results were obtained on the possibilities of disinfecting water by simple exposure to the solar radiation [3].

With the aim of verifying the suitability of this method in the real field conditions, the United Nations University financed and coordinated research projects in several different developing countries. This paper contains the results obtained in the Northern coastal region of Peru.

The viability of the solar water disinfection into a determined area depends on two main questions: i) the existence of appropriate environmental conditions and ii) the reliability of the method. Both had to be considered in this work. Part I of this paper is a summary of the studies carried out on the following relevant characteristics of the environment: general, economical and social characteristics of the area, water-related morbidity and mortality, quality of the water sources, transportation and handling, available solar radiation. In Part II some experimental results on the solar disinfection of local specimens of water are reported.

PART I - STUDIES ON ENVIRONMENTAL CONDITIONS

General Economical and Social Characteristics:

The area considered lies in Northern Peru at a Latitude between 4 and 6 degrees South. It encloses two typical zones: the arid Pacific coast and the Andes mountains, which are representative of the whole Peruvian territory, excluding the Amazon region (Figure 1).

Agriculture is the main activity of the 38% rural population. In the coastal area, it develops on narrow bands along two small rivers (Chira and Piura), surrounded by the Sechura Desert. Over the Andes, agriculture is based on the summer rains. Due to a number of reasons the incomes of the farmers are low and poverty is widely diffused. Irrigation is a main problem: the cultivated soil in the coastal region is limited by scarce underground water and poor river flows, whereas on the Andes, irregular rain and frequent drought prevent satisfactory levels of production. Progressive desertification, low technical level, lack of diversification in the agricultural production and scarce commercial channels are further major limitations.

According to official information, 62% of the houses have no drinking water and sanitation system nor electricity. This includes the whole rural population [4]. The official infant mortality is reported to be close to 67%. [5]. An important fraction of the rural population lives in isolated houses: 64% in the Piura River valley and 43% in the Chira valley [6].

A recent study of a typical village of 500 families [7] showed that only 55% of the households cultivate their own plots, which is less than 1 hectare for 81% of them. The average family income, including that from some handicrafts as well, is less than U.S.$ 1 per day for 80% of the families. Illiteracy reaches 42%: only one third of the children go to school. 40% of the population is less than 14 years of age: one in four children dies before reaching adulthood.

WATER-RELATED DISEASES

The available official morbidity data indicate a prominent presence of water related diseases in the whole country [8]. Between 1979 and 1982 "Gastroenteritis, enteritis and other diarrhoeas" were the first item in Peruvian morbidity, with about 143,000 reported cases in 1982 and an average annual growth rate between 25% and 78%. The situation of the other water-borne diseases is shown in Table 1, where the etiologic agents which are to be considered in water disinfection, are also indicated.

In the Dept. of Piura, "Undefined intestinal infections", which usually mean dehydration due to diarrhoea, are the second cause of morbidity and mortality, after pneumonia. They are responsible for 8.3% of infant morbidity and 21.9% of infant mortality [5].

QUALITY OF THE WATER DISTRIBUTED BY THE PUBLIC SERVICE

Between 1960 and 1980, 948 public systems of drinking water distribution were installed in large Peruvian villages (400-2,000 inhabitants). In 1980, only 58% of them were in

TABLE 1 MORBIDITY (NUMBER OF REPORTED CASES IN 1982) OF WATER-BORNE DISEASES IN PERU, AVERAGE ANNUAL GROWTH BETWEEN 1979 AND 1982 [8] AND CORRESPONDING ETIOLOGIC AGENTS [9].

Diseases	Cases	Growth	Etiologic agents
Gastroenteritis, enteritis and other diarrhoeas	142,831	63%	Yersinia enterocolitica E. coli Campylobacter fetus
Typhoid, paratyphoid	23,868	32%	S. typhosa S. paratyphi
Bacillary dysentery	7,618	12%	Shigella spp.
Hepatitis virica	7,191	6%	Enterovirus

operation. The main problems were related to inadequate maintenance, lack of training, habits and improper design [10].

In the Dept. of Piura, 33 systems were installed in the same period, 23 of them in the coastal region (drilled wells with motor-pump and reservoir) and 10 in the Andes zone (gravity type). Forty-five percent of the pumping systems were found damaged in 1980, the remaining were operated intermittently because of the high cost of the fuel. It is estimated that about 30,000 rural people are supplied water by public distribution services at present, which represent about 6% of the rural population in the Department of Piura.

Bacterial contamination of water is common in the public distribution services, due to the lack of maintenance and control, intermittent operation, transportation from the drinking-fountains to the house, etc. Bacteriological analysis carried out in 6 public systems over the period 1980-1985 indicated Coliform bacteria contents ranging between 20 and 80 units per 100 ml in most cases and reaching 130-350 units in the worst cases. Total bacteria ranged between 400 and 4500 units/ml in all cases.

QUALITY OF THE WATER OBTAINED FROM RURAL SOURCES

In the arid coastal region water is scarce and highly contaminated. More than 90% of the rural population has no access to any public services and obtain water directly from the rivers, irrigation channels, shallow wells and puddles. The latter two sources are supplied by surface water, drained from irrigated soils. The underground water is salty up to a depth of 70 to 120 metres.

When a relatively short distance is to be covered between the source and the house, the water is carried by the villagers themselves. Otherwise, it is transported by tankers, carts or animals, mainly using barrels. In this case it is sold to the households at US $5-10 per cubic metre.

The water is usually heavily contaminated. Bacteriological analysis on 10 rural sources over the period 1980-1985, showed a Coliform content of 100-300 units per 100 ml. The total bacteria content ranged widely (700-150,000/ml). The Piura river, which supplies water to most rural population, maintains a content of E. coli of 140-280 units/100 ml.

HANDLING OF WATER

The habits in handling and storing water are to be carefully considered in order to establish the viability of the solar water disinfection. If minor habit changes are needed to apply the technique, particularly with respect to the containers to be used, there are better chances to succeed.

Independently of its origin (public drinking-fountain, natural source or retailer), the water is transported to the house in light vessels of 10-20 litres: tins and plastic pails are mainly used. The distance to be covered, usually by women and children, varies between few meters to a few kilometers. The water is then stored in big pots of about 50 litre capacity. Little care is usually devoted to prevent further contamination during the transportation and storage.

Low cost tins, originally obtained as containers of cooking oil, are widely used for water. They are frequently replaced and maintained in good condition. A theoretical comparison [11] between a transparent container and a perfectly reflecting cylindrical vessel opened on its surface, has shown that the number of light rays crossing the unit volume is two fold greater inside the latter, when both are exposed to the same radiation. This theoretical result does not depend on the radiation direction (direct or diffuse), nor on the shape of the containers. This indicates that reflecting vessels, like tins or thermos, should not be discarded "a priori" for solar disinfection purposes.

SOLAR RADIATION

Peru lies between the latitudes of 4 and 18° S. High and constant solar radiation is generally available both along the whole arid coast, except a small area around Lima, and over the Andes mountains, except some rainy days in summer (January-March). The annual average solar radiation for ten main Peruvian cities is reported in Table 2 [12].

The Piura city data, available for the decade 1976-1985 (Figure 2), indicates a slight seasonal fluctuation in the solar radiation, which is typical of the whole Peruvian coast. A minimum monthly average of 4.3-5.5 kWh/m2.day correspond to June-July, whereas a maximum monthly average of 5.5-7 kWh/m2.day is reached in October-November. During 1985, which may be considered a representative average year, a daily solar radiation below 1.5 kWh/m2 was reported for two days only.

The situation is quite different on the Andes mountains, due to the presence of a rainy season in January-March. The monthly average solar radiation maintains quite high values, nevertheless the occurrence of several consecutive cloudy days is not unlikely [13].

TABLE 2 ANNUAL AVERAGE SOLAR RADIATION IN 10 PERUVIAN CITIES, LOCATED AT DIFFERENT LATITUDES AND ALTITUDES ABOVE SEA LEVEL.

City	Latitude	Altitude (m)	Solar radiation (kWh/m^2.day)
Arequipa	16°24'S	2,380	6.7
Puno	15°50'S	3,850	6.6
Huancayo	12°04'S	3,270	6.4
Moquegua	17°12'S	1,470	5.9
Ayacucho	13°10'S	2,750	5.8
Chiclayo	06°46'S	coast	5.2
Ica	14°04'S	coast	5.1
Cuzco	13°31'S	3,420	5.1
Piura	05°12'S	coast	5.0
Trujillo	08°07'S	coast	4.8

PART II - EXPERIMENTAL WORK

With the aim to verify the viability of the solar water disinfection in the conditions of the Peruvian Northern coastal region, several samples of contaminated water were exposed to solar radiation and analyzed to determine its effects on the bacteria content.

A variety of local conditions have been taken into account. Water samples of the Piura river, which is the main water source used in rural areas, have been tested. Tins and pails, widely used by the villagers, have been employed for exposure to the sun and compared to transparent bottles, which are usually recommended.

The effect of the temperature on the bacteria survival and the effect of using vessels with reflective surface on the purification process was also investigated.

EXPERIMENTAL METHOD

Quality of water sources:

"Los Egidos", a village of 1000 people located 10 km North of Piura city, was selected as a typical village whose water is supplied by natural sources. No public system is available and water is obtained by three sources: a) Piura river, at a distance of 150 m from the village and b) two wells (called "Big well" and "Small well"). Both are poor shallow wells located at a distance of 300 m from the village.

Physical and chemical analyses of the "Big well" and of Piura river were carried out in November 1986. Several samples of both sources were withdrawn for bacteriological analysis between November 1986 and May 1987.

Specimens:

Four specimens have been used for the solar disinfection tests. Three of them (A, B and C) were artificially contaminated, whereas the fourth (D) was directly obtained from the same site from the Piura River, where "Los Egidos" villagers get their water. Details on the preparation of the specimens are reported in Table 3.

Measurement techniques

Exposure of contaminated water samples to the sun was carried out in the interior court of the laboratory, in order to analyze each sample immediately. The time and duration of the exposure to sunlight are indicated in the "Results" section, together with the withdrawal schedules. In all cases, after exposure, the samples were kept under room conditions for about 24 hours and then the same analyses were repeated.

TABLE 3 DETAILS OF THE SPECIMENS USED. TOTAL BACTERIA (TB) ARE INDICATED IN THOUSANDS/ml; TOTAL COLIFORMS (TC) AND E. coli (EC) ARE IN UNITS/ml.

Specimen	Source	Preservation	Dilution	Bacteria content		
				TB x 10^3	CT	EC
A	puddle + urine	24 hours refrigerator	1:300 distilled water	49.3	80	80
B	city sewage	24 hours refrigerator	1:100 drinking water	51	70	51.5
C	city sewage	tested immediately	1:200 drinking water	45.5	65	n.d.
D	Piura river	tested immediately	none	82	76	n.d.

Total bacteria were determined by the standard plate count procedure. The membrane filter method was used for Coliform bacteria in specimens A, B and C , while the multiple tubes method was used for specimen D. The solar radiation was measured during exposure by a SIAP SO-2800 bimetallic pyranograph.

Comparison Between Sunlight, Room Light and Darkness: Specimen A was placed in 2 litre plastic bottles. Three transparent bottles were exposed to sunlight and one to room light. A green bottle was placed in a closed dark cupboard.

Comparison Between Transparent Bottles and Tins: Specimen B was placed in 2 litre plastic bottles and 18 litre tins. Three transparent bottles were exposed to sunlight and

one to room light. Two tins were used: a new one, with very good reflecting surface, and an old one, heavily oxidized.

Effect of Exposure Time: The three bottles of the previous test were withdrawn from the sun after exposed for 40, 80 and 120 minutes respectively. Then they were kept for 24 hours at room lighting conditions.

Effect of the Temperature: Five 2 litre transparent plastic bottles filled with specimen C were used. Four bottles were exposed to sunlight; two of them were prevented from warming by the use of a fan. The last bottle was maintained at room lighting conditions.

Comparison Between Transparent and Reflective Containers: At the same time intervals as above, 2 litres of specimen C were exposed to the sunlight inside a cylindrical plastic jar, whose walls were covered by aluminum foil.

Exposure of the River Water in Different Containers: Specimen D was exposed to the sunlight in three different containers: two 2 litre transparent plastic bottles, a 20 litre tin and a 12 litre orange plastic pail.

RESULTS

Quality of Water Sources:

The physical and chemical analysis of the water used in "Los Egidos" village indicated that the Piura river water is suitable for human use (Class 1, Sub-class 1A, according to the Natural Water Classification Criteria), whereas the water of the "Big well" is not suitable, because of the high content of Nitrites (0.25 mg/l), Ammonia (0.6 mg/l) and Phosphates (0.91 mg/l). The river water shows a very high turbidity. The results of the bacteriological analysis are shown in Tables 4 and 5, showing a widely variable contamination of all sources.

TABLE 4 TOTAL BACTERIA (TB, THOUSANDS/ml), TOTAL COLIFORM (TC, UNITS/ml) AND E. coli (EC, UNITS/ml) IN THE PIURA RIVER WATER, AT "LOS EGIDOS" BANK AND THE CENTER OF THE RIVER.

	Bank "Los Egidos"			Center site 1			Center site 2		
Date	TB $x10^3$	TC	EC	TB $x10^3$	TC	EC	TB $x10^3$	TC	EC
21/11/86		0.3	0.03						
2/12/86		0.06	0.02						
9/12/86				0.2	0.43	0.09	0.4	0.93	0
27/02/87				0.8	5.3	0.6	0.5	1.1	0.92
4/05/87	58.8	>11	1.1						
12/05/87	82	76							

TABLE 5 TOTAL BACTERIA (TB, THOUSANDS/ml), TOTAL COLIFORMS (TC, UNITS/ml) AND E. coli (EC, UNITS/ml) IN THE WELLS USED BY "LOS EGIDOS" VILLAGERS

Date	"Big well"			"Small well"		
	TB	TC	EC	TB	TC	EC
21/11/86		0.07	0.02		0.01	0
02/12/86		0.04	0		0.5	0.07
04/05/87	66	>11	>11	86.4	>11	2.9

Comparison Between Sunlight, Room Light and Darkness

The effect of exposure to sunlight, room lighting conditions and darkness on the E. Coli and on total bacteria is shown in Table 6 and Figure 3. In the specimen exposed to sunlight, E. coli was completely eliminated after an exposure time between 30 and 60 minutes and no re-growth occurred after 18 and 25 hours in room conditions, in spite of the low values of solar radiation (Figure 3). In room light and darkness conditions, E. Coli is not eliminated and reached very high values after 25 hours.

TABLE 6 TOTAL BACTERIA (TB, THOUSANDS/ml) AND E. coli (EC, UNITS/ml) AFTER INCREASING TIME IN SUNLIGHT, ROOM LIGHT AND DARKNESS (SPECIMEN A)

Time (h)	Sunlight		Room light		Darkness	
	TBx10^3	EC	TBx10^3	EC	TBx10^3	EC
11-15'	49	80	49	80	49	80
11-45'	41	11	37	40	37	80
12-15'	34	0	34	35	30	70
12-45'	27	0	30	30	28	67
13-15'	26	0	26	30	34	67
13-45'	22	0	22	28	41	67
14-15'	7	0	20	28	43	63
14-45'	1	0	20	29	30	60
15-15'	6	0	20	26	30	60
Day after	Room light		Room light		Darkness	
09-00'	235	0	290	32	264	53
16-30'	>1600	0	>1600	>200	>1600	74

NOTE: Total bacteria were reduced by exposure to sunlight; they re-grew to similar high values in all specimens after one night in room conditions.

Comparison Between Transparent Bottles and Tins

The complete elimination of E. coli was achieved between 30 and 45 minutes in specimens exposed to sunlight in transparent bottles and in the old tin, whereas in the new tin 75-90 minutes were required (Table 7 and Figure 4). (Surprisingly, E. coli disappeared in the specimen maintained in room light after about 2 hours). In no case was re-growth observed after 24 hours under room light.

Total Coliforms were completely eliminated after 75-90 minutes when exposed to sunlight in transparent bottles and no re-growth occurred. In both tins after 2 hours of exposure all Coliforms were nearly eliminated. No re-growth was observed in the new tin, whereas a moderate re-growth occurred in the old tin after 24 hours under room light.

Total bacteria were strongly reduced during exposure to the sunlight in transparent bottles. The exposition in tins produced only slight differences with respect to the sample maintained at room light. Solar radiation was measured and found to vary between 930 and 1000 W/m2.

TABLE 7 TOTAL BACTERIA (TB, THOUSANDS/ml), TOTAL COLIFORMS (TC, UNITS/ml) AND E. coli (EC, UNITS/ml) AFTER EXPOSURE TO SUNLIGHT OR ROOM LIGHT IN DIFFERENT CONTAINERS (SPECIMEN B).

	Sunlight (930-1000 W/m2)											
	Transp. bottle			New tin			Old tin			Room light		
Time (h)	TB $x10^3$	TC	EC	TB $x10^3$	TC	EC	TB $x10^3$	TC	EC	TB $x10^3$	TC	EC
11-15'	51	70	51	51	70	51	51	70	51	51	70	51
11-30'	-	22	20	-	46	30	-	30	25	-	48	45
11-45'	36	21	17	42	19	19	45	15	10	48	41	40
12-00'	-	17	0	-	16	6	-	15	0	-	36	30
12-15'	24	3	0	34	14	3	38	11	0	46	32	28
12-30'	-	1	0	-	11	1	-	9	0	-	32	27
12-45'	11	0	0	32	10	0	38	6	0	45	30	27
13-00'	-	0	0	-	6	0	-	3	0	-	10	0
13-15'	7	0	0	31	3	0	32	1	0	40	10	0
Day after					Room light							
13-15'	89	0	0	260	0	0	260	12	0	224	54	0

Effect of Exposure Time

As indicated above, Coliform bacteria were completely eliminated after 2 hours of exposure to sunlight in transparent bottles (Table 8), and did not re-grow after 24 hours

in room conditions. Coliforms, however, were not completely eliminated in samples exposed 40 and 80 minutes.

Total bacteria were progressively reduced by exposure to sunlight. Nonetheless, the final content of bacteria after 24 hours in room light showed a very slight dependence on the exposure time.

TABLE 8 TOTAL BACTERIA (TB, THOUSANDS/ml) AND TOTAL COLIFORMS (TC, UNITS/ml) AFTER DIFFERENT TIME OF EXPOSURE TO SUNLIGHT OR ROOM LIGHT AND AFTER 24 HOURS TO ROOM LIGHT (SPECIMEN B).

	Sunlight (930-1000 W/m2)						Room light	
	40 min		80 min		120 min		120 min	
Exposure time	TB x10^3	TC	TB x10^3	TC	TB x10^3	TC	TB x10^3	TC
Before exposure	51	70	51	70	51	70	51	70
After exposure	36	21	24	1	7	0	40	10
After 24 hours in room light	99	15	95	13	89	0	224	54

Effect of Temperature

In the Specimen C, the complete elimination of the Coliforms were achieved in 60-120 minutes in transparent bottles, with no re-growth in the dark (Table 9 and Figure 5). The total number of bacteria was reduced to 10% during exposure, but increased one hundred folds in the night.

No significant change in the elimination of bacteria were observed when the sample was prevented from warming by the use of a fan. The temperature rose from 31°C to 36.3°C during 5 hours of exposure to the sun, whereas in the normally exposed sample the temperature reached 42.8°C (Figure 5).

Transparent vs Reflective Container

In the same test as above (Table 9 and Figure 5), specimen C was exposed in a container covered by aluminum foil. Compared to transparent bottles it was observed that Coliform bacteria were eliminated at a lower speed and some re-growth was observed at night. The reduction of the total bacteria was both quicker and stronger in the reflective container, resulting in a smaller content of bacteria the day after.

TABLE 9 TOTAL BACTERIA (TB, THOUSANDS/ml) AND TOTAL COLIFORM (TC, UNITS/ml) AFTER EXPOSURE TO SUNLIGHT IN DIFFERENT CONDITIONS OR MAINTAINED IN ROOM LIGHT (SPECIMEN C). THE SOLAR RADIATION DURING THE EXPOSURE IS SHOWN IN FIGURE 5.

	Sunlight						Room light	
	Transparent bottle		Trans. bottle cooled by fan		Reflective container		Transparent bottle	
Time (h)	TB $x10^3$	TC	TB $x10^3$	TC	TB $x10^3$	TC	TB $x10^3$	TC
09-55'	45.5	65	45.5	65	45.5	65	45.5	65
10-10'	25	60	25	60	37	64	43	64
10-25'	24	51	22	58	33	62	40	65
10-55'	20	0.7	18	1	4.8	47	37	45
11-55'	11	0	14	0.02	3.6	1.3	34	40
13-55'	4.4	0	4.4	0	3.3	0.95	64	20
Day after				Room light				
08-00'	510	0	500	0	300	4	1600	(*)

(*) Too numerous to be counted.

Exposure of the River Water in Different Containers

Total bacteria and total Coliforms after 3 and 5 hours of exposure are presented in Table 10, and solar radiation values are shown in Figure 6.

Coliform bacteria were apparently eliminated in transparent bottles and strongly reduced in the other containers. Nevertheless, they were still present in all cases after one night.

The total bacteria content was reduced by the sunlight in the water contained in transparent bottles. On the contrary, little differences were observed between the water exposed to the sunlight in a tin or pail, compared to the room light conditions.

DISCUSSION

Quality of the water Sources

The bacteriological analysis of three sources of water used in "Los Egidos" village indicated a very high variability of bacterial contamination. In the case of the river bank, the watering of droves of cattle produces a very strong local contamination, which dilutes later. A similar effect is produced by people and animals pouring in shallow wells.

In any case, this indicates the poor significance of a single sample in evaluating rural sources of water. In most cases, a thorough testing of the source should be considered and many samples withdrawn at different times, simulating real supply conditions.

TABLE 10 TOTAL BACTERIA (TB, THOUSANDS/ml) AND TOTAL COLIFORMS (TC, UNITS/ml) AFTER EXPOSURE TO SUNLIGHT OR ROOM LIGHT OF PIURA RIVER WATER (SPECIMEN D) IN DIFFERENT CONTAINERS. THE SOLAR RADIATION DURING EXPOSURE IS INDICATED IN FIGURE 6.

	Sunlight						Room light	
	Transparent bottle		Tin		Plastic pail		Transparent bottle	
Time (h)	TB $x10^3$	TC	TB $x10^3$	TC	TB $x10^3$	TC	TB $x10^3$	TC
09-55'	82	76	82	76	82	76	82	76
12-55'	7	0	18	11	21	11	16	11
14-55'	2.7	0	17	4.6	22	0.75	32	11
Day after				Room light				
08-00'	35	2.4	100	4.6	80	0.93	90	4.6

Coliform Bacteria

The elimination of Coliform bacteria after exposure to the sunlight has been clearly verified. Coliforms are definitively eliminated from the sewage contaminated water after 1-2 hours exposure to direct sunlight in transparent bottles and after slightly more than 2 hours in tins. No re-growth occurs after 24 hours in room light. E. coli seems less resistant, being eliminated in 30-60 minutes of exposure to sunlight in transparent bottles and 30-90 minutes in tins.

There is a substantial agreement with the results of Acra et al. [3], who reported a destruction time of 80 minutes and 75 minutes for Coliforms and E. coli respectively. According to Acra, S. typhosa and S. paratiphy B are eliminated in 60 minutes and 90 minutes respectively. This seems to indicate good possibilities of utilizing the solar radiation for drinking water disinfection in our conditions, taking into account the high and more or less constant values of the solar radiation for considerable number of hours during the day (Figure 2). Unfortunately, no information is available at present on other etiologic agents, which are important in this area (Table 1).

In the case of Piura river water the exposure to sunlight strongly reduced Coliform bacteria, but failed to eliminate them completely. This is probably due to the very high turbidity of the water that prevented the transmission of solar radiation, especially in bulky containers. Filtering before exposure should overcome this problem.

Total bacteria

Total bacteria are reduced by exposure to sunlight, but they are not completely eliminated. In artificially contaminated samples maintained for 24 hours at room light, total bacteria increased to very high values (between 5 and 30 fold the initial contamination). Samples exposed to sunlight in transparent bottles and then maintained for 24 hours at room light showed a reduced re-growth of total bacteria, up to about one third of non-exposed samples (see Tables 5-8,). This figure seems to be quite independent of the kind of contamination (whether artificial or natural) and on the exposure time (Table 6).

An important exception to this was found in specimen A, where the same number of total bacteria were observed the day after, independently of the exposure to sunlight, room light or darkness. This suggest that bacteria living in shallow puddles normally exposed to the sunlight may be more resistant to the solar radiation.

Different Containers Used for the Exposure:

Tins or pails may probably be used for solar water disinfection when high intensity solar radiation is available, however, the germicidal effect seems weaker than that observed when transparent bottles were used. In samples exposed to the sunlight in tins or pails total bacteria after 24 hours in room light were the same as in non-exposed samples (Tables 5 and 8), or three fold greater than samples exposed in transparent bottles.

However, the germicidal effect appears to increase with a container having good (internal) reflective surfaces. The sample exposed in the container covered by aluminum foil and then maintained 24 hours in room light, showed about one half the total bacteria content, with respect to the sample exposed in transparent bottle. This seems to confirm the theoretical prediction [11] that the elimination of bacteria proceeds at double speed in reflective containers than in transparent bottles.

Effect of Temperature

No effects of the water temperature have been observed until the temperature reaches 42.8°C. Nevertheless, if higher temperature could be reached, the pasteurization should join to the solar radiation germicidal effect. An open mouth thermos, covered by glass or transparent plastic, could be an optimum device to combine light and heat for particular disinfection purposes, like preparing oral re-hydration solutions or supplying rural health centers.

CONCLUSIONS

Environmental Conditions:

With respect to the viability of the solar water disinfection in Peru, and in particular in the Dept. of Piura located over the arid Northern coast, the main conclusions are as follows:

a) It may be estimated that more than 90% of the rural population has no access to clean drinking water. Water for domestic use is supplied by contaminated sources like rivers, irrigation channels, shallow wells and puddles.

b) Water associated diseases (gastro-enteritis, typhoid, paratyphoid, bacillary dysentery and hepatitis virica) are widely diffused. Gastro-enteritis, enteritis and other diarrhoeas are responsible of 21.9% of infant mortality, which is 67% in the Department of Piura.

c) The solar radiation intensity is very high (4.3-7 kWh/day) during the whole year. Cloudy days are very infrequent.

d) Tins and plastic pails of 10-20 litres are used for transportation and handling of the water. If the same containers could be effective for the solar disinfection, the diffusion of the method should not meet insurmountable obstacles. Transparent containers seem difficult to introduce because of their low availability, too small a capacity, less durability and high cost.

Effectiveness of Solar Water Disinfection:

The experimental work carried out to verify the effectiveness of the water disinfection by simple exposure to solar radiation provided the following indications:

a) The rural sources of water show a wide variability in their bacterial contamination. Consequently, the evaluation of any chosen source must be based on many samples, withdrawn over a long period of time, taking into account the whole running of the source.

b) The elimination of Coliform bacteria, obtained in a variety of conditions, seems to indicate that solar disinfection has good chances of being effective in many local situations. It is to be noted that most rural sources showed much lower contamination levels than the specimens used in this work.

c) Total bacteria are reduced, but not completely eliminated by solar radiation. Furthermore, they tend to re-grow after exposure, frequently reaching very high values. Consequently, it is critical to make sure that no dangerous organism survives the disinfection process.

d) The effectiveness of the technique has to be evaluated step by step, considering the following main factors: amount and type of the bacterial content, turbidity of the water, characteristics of available containers, local meteorological conditions. The conditions prevailing in this area indicate that one day of exposure to sunlight in locally available tins or pails may be sufficient to disinfect the water in some cases. Turbid water should be filtered prior to its exposure to solar radiation.

e) More experimental work is needed to establish standard procedures for solar water disinfection. No information is yet available on the germicidal effect of the sunlight on some etiologic agents which are important in this area (Yersinia enter., Campylobacter fetus, Shigella spp., Enterovirus). Furthermore, the laboratory results should be verified under field conditions.

f) No contribution of water temperature on the elimination of bacteria have been found below 42.8°C. Higher temperatures should be reached to take advantage of pasteurization.

g) Containers with good internal reflective surfaces seem to provide a faster elimination of bacteria in agreement with theoretical predictions.

FUTURE WORK

Future work should involve both laboratory research and field pilot projects. In particular, the following activities are recommended:

a) Experimental determination of the germicidal effect of sunlight on all important etiologic agents.

b) Experimental comparison between the elimination times of bacteria in laboratory conditions, with respect to field conditions.

c) Experimentation of a prototype container for solar water disinfection, based on an open mouth thermos with transparent cover.

d) Field pilot projects, including characterization of the sources of water, experimental determination of the disinfection procedure, training of the villagers, monitoring of the disinfected water, and monitoring of the water associated diseases.

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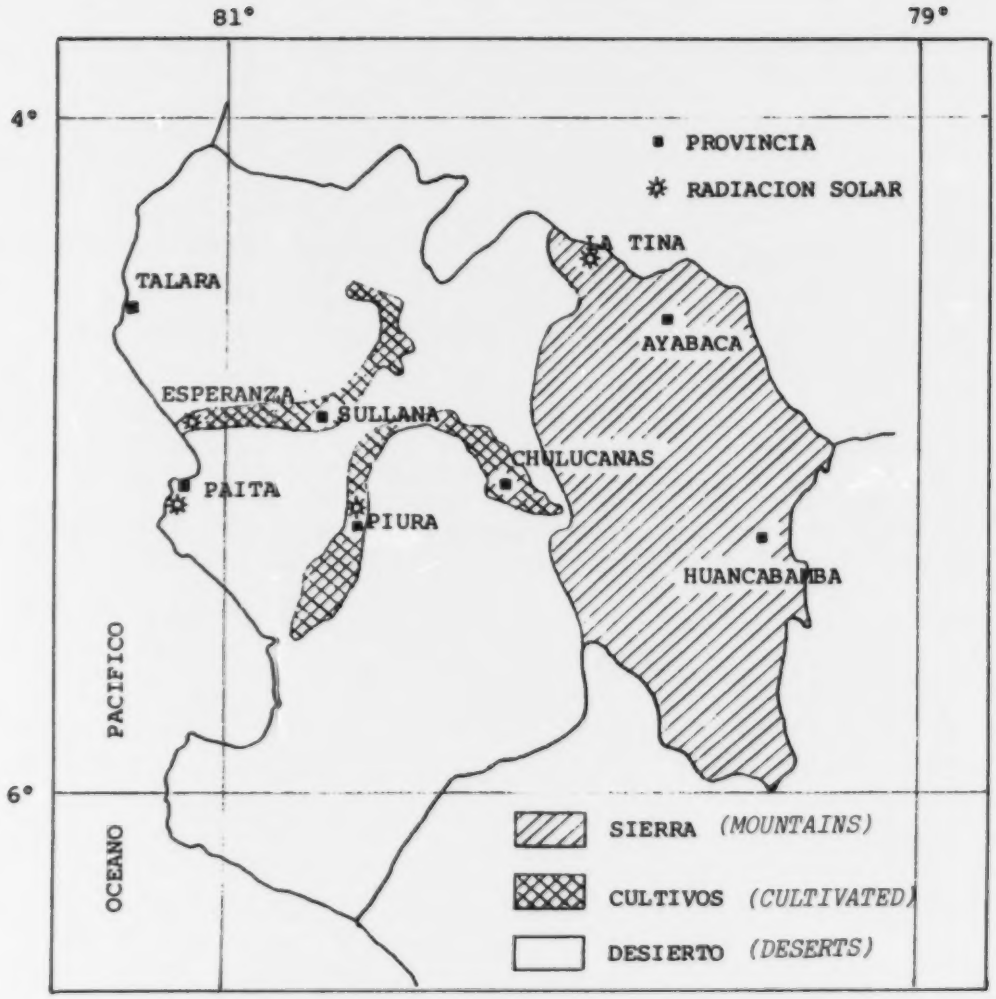

FIGURE 1. Map of the Department of Piura

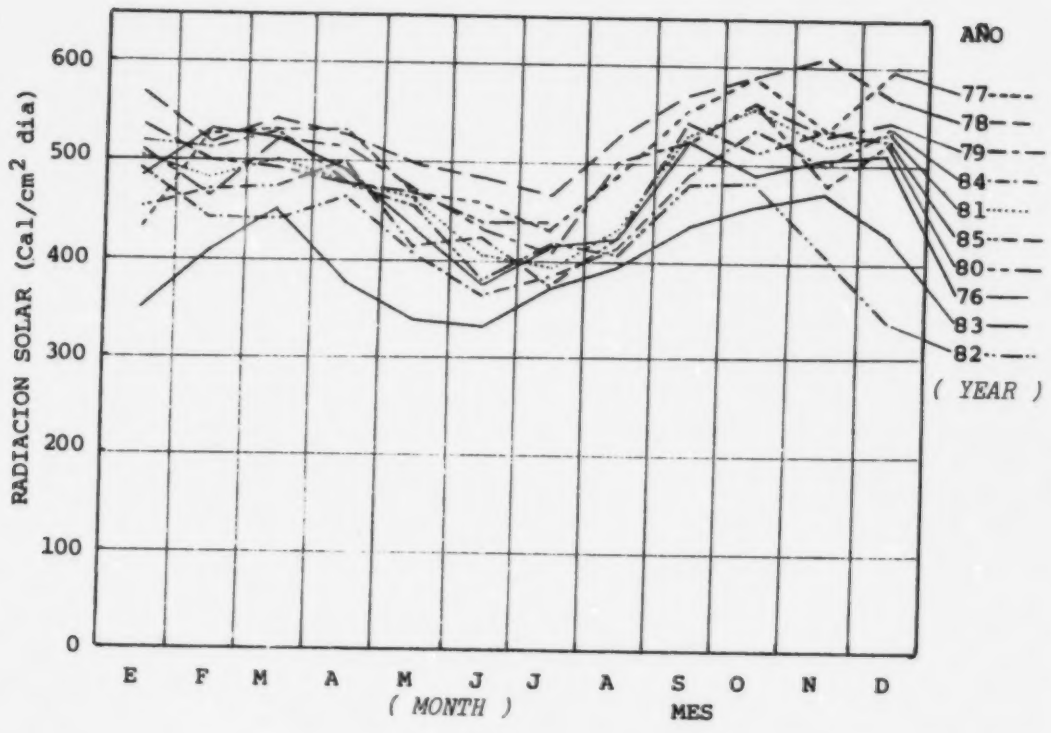

FIGURE 2. Monthly average solar radiation in Piura city during the decade 1976-1985 (Miraflores climatological station - Piranograph SUESS type "Black Chart N. 158K).

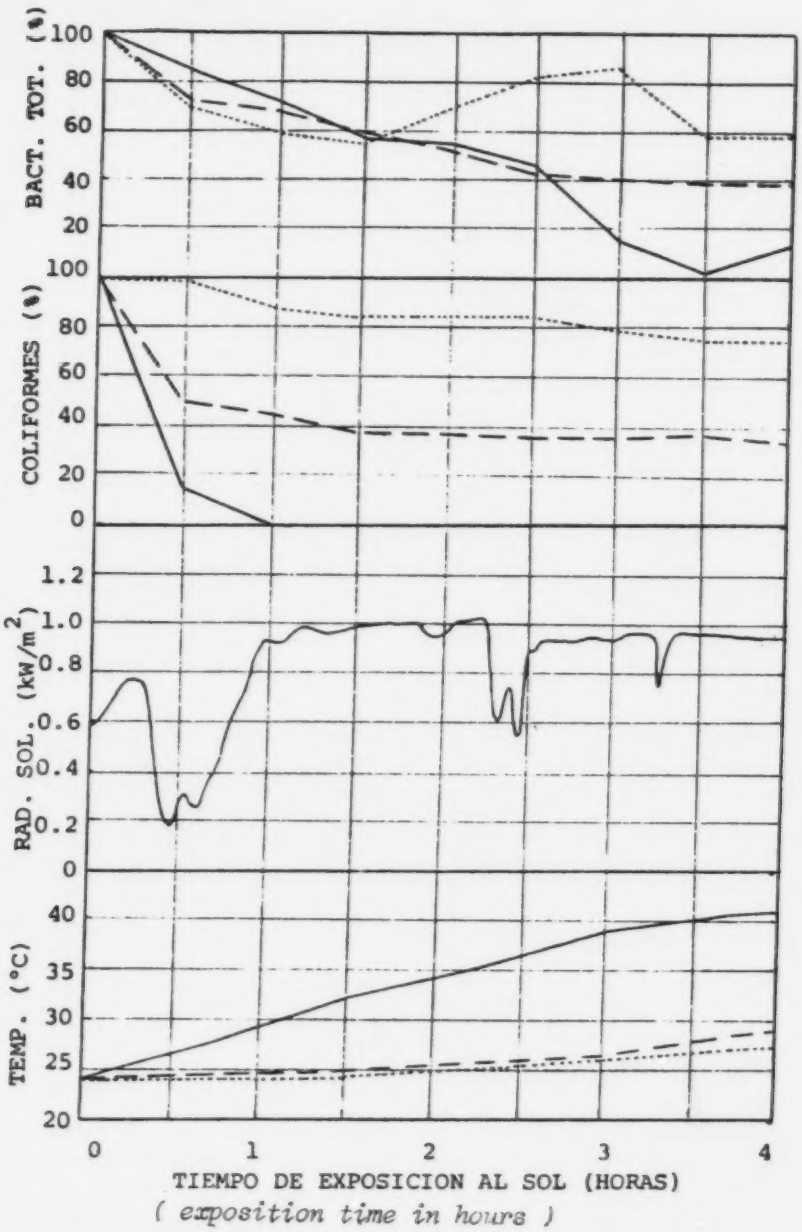

FIGURE 3. Specimen A: residual total bacteria and E. Coli after different exposure time in direct sunlight (solid line); room light (dashed line) or in complete darkness (dotted line). Solar radiation and temperature during the exposure are also shown.

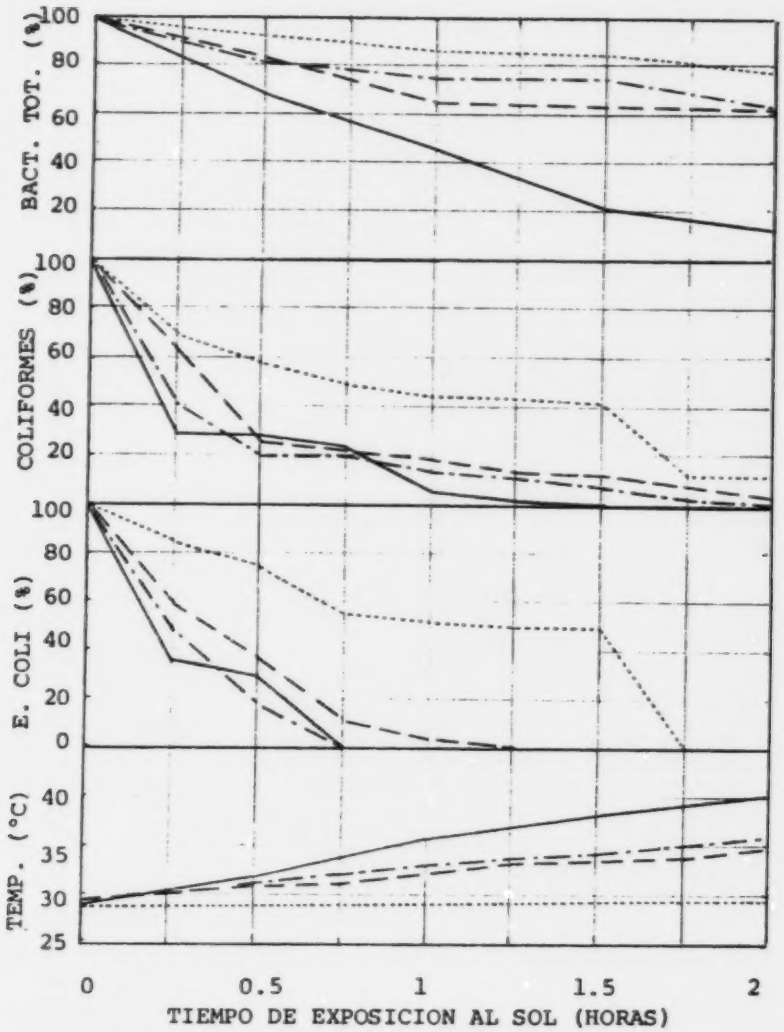

FIGURE 4.

Specimen B: residual total bacteria, total Coliforms and E. Coli after different exposure time in direct sunlight in transparent bottles (solid line); in a new tin can (dashed line); in an old tin can (dashed and dotted line) or in room light (dotted line). Temperature during each period of exposure is also shown.

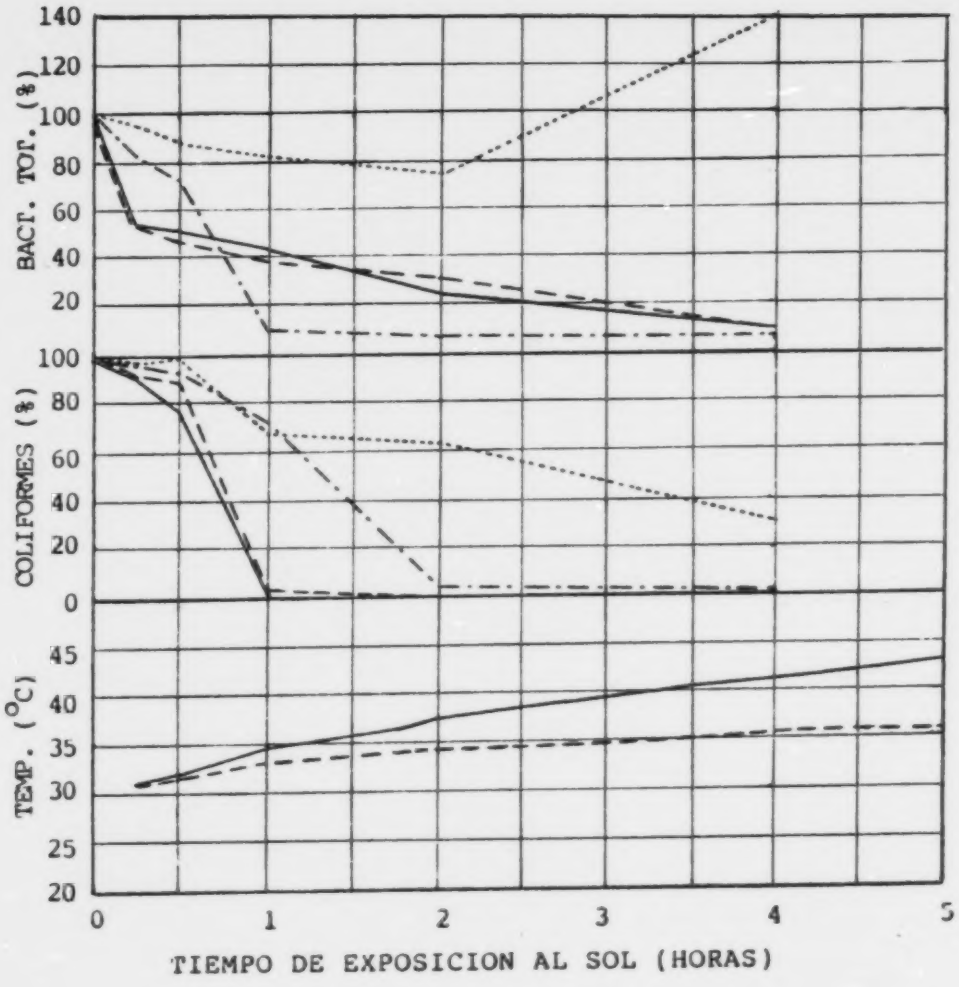

FIGURE 5. Specimen C: residual total bacteria and total Coliforms after different exposure time in direct sunlight in transparent bottles (solid line); in transparent bottles cooled by a fan (dashed line); a cylindrical container covered with aluminum foil (dashed and dotted line) or in room light (dotted line). Temperature of cooled and non-cooled transparent bottles are also shown.

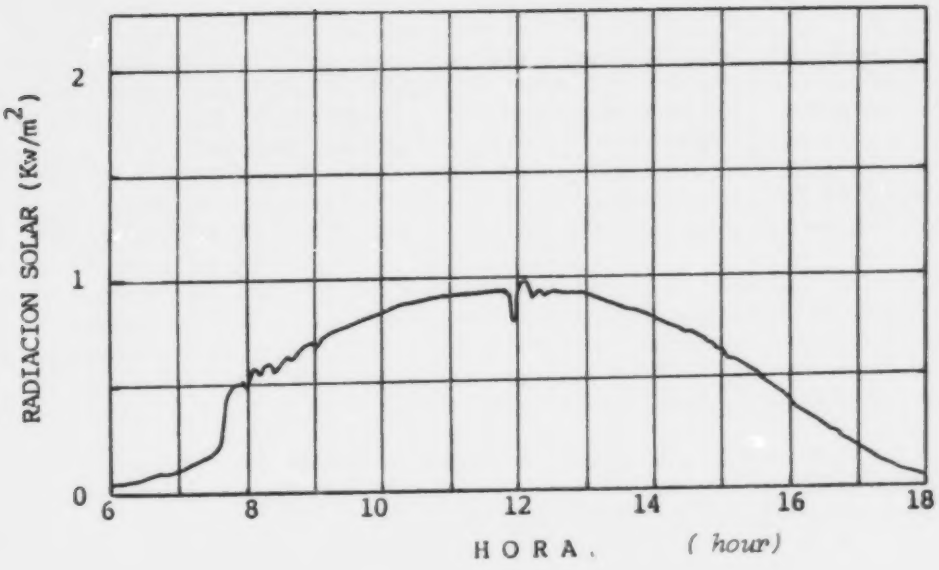

FIGURE 6. Solar radiation on 12 May 1987, when Specimens C and D were tested.

SOLAR WATER PURIFICATION IN COLOMBIA[1]

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INTRODUCTION

The Risaralda Department, one of the largest coffee producing provinces of Colombia is located between 4°39' and 5°39' of latitude (north) and 75°23' to 76°18' of longitude (west). Pereira, the capital of the Department, has a population of 287,000, an average altitude of 1400 m over sea level, an average precipitation of 2750 mm and average relative humidity of 85%. The monthly average daily total solar radiation at Pereira varies from 2.48 Kwh/m^2 to 3.41 Kwh/m^2 (February). Whereas the monthly average daily direct solar radiation varies from 0.99 Kwh/m^2 (November) to 1.55 Kwh/m^2 (June).

Most of the rural population in the Risaralda area is directly or indirectly engaged in the production of almost 20 million pounds of coffee yearly. Other crops such as sugarcane, cassava, corn and sorghum are also grown. About 50% of the population of the Risaralda Department has no direct access to treated water and even in the city of Pereira, 20% of the population has no access to treated water.

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Pereira, like almost all intermediate and large cities of Colombia has experienced an invasion of dwellers from rural areas in the past 30 years. Most of these people settled in informal areas, of which, some are presently an integral part of the city. Other areas are still "favelas" with no connection to the services of the city. In these areas the residents are hoping for the legislation of the land tenure and services in the near future. The Project concentrated in the informal settlement

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[1] This summary was prepared based on a research report sent by the authors to the United Nations University (Tokyo, Japan) entitled "Solar Water Purification in Coffee Growers Climate".

belt of Pereira in which most of the population uses untreated water from open fountains, open creeks and self made gravity conduction systems based on rivers, creeks and fountains.

The possibility of disinfecting drinking water by exposing it to solar radiation for a certain period of time was first explored by Professor Acra and his associates in Beirut, Lebanon. However most of their experiments were conducted under very good solar radiation conditions. In order to examine the feasibility of this simple water disinfection approach in an area with relatively poor insolation characteristics it was decided to conduct similar experiments in the Pereira area of Colombia.

METHODOLOGY

During the first few months several tests were made with naturally and artificially contaminated waters. These tests basically served to develop a standard procedure for analysis, to redefine certain objectives, to determine the need of special equipment and to find a usable and understandable field technique. The care of the project concentrated in the development of appropriate equipment and direct field work on actual households using the normally contaminated water used for human consumption. Seven individual sites were examined. In all, eleven sources, from which these communities were actually drinking the water, were analyzed as per the following procedures (see Table 1).

Initial Tests:

At 10:00 A.M., samples of the water that was currently being used by the households were taken and then divided into two parts. The first part was directly inoculated into the culture media and its incubation was initiated immediately with the help of a portable incubator.

The second part of the sample was exposed to local solar radiation in a transparent glass container (a popular liquor bottle; Aguardiente Cristal) placed over a diffuse white reflector.

At midday, a sample was taken from the exposed bottle and was once again inoculated into the culture media and placed into the portable incubator.

At 14:00 hours two samples were taken from the exposed bottle, the first one was inoculated into the culture media and the second one was stored for further analysis after 24 hours or in some cases after 8 or 15 days.

Later in the afternoon, the samples were transferred to the laboratory incubator and the standard three test tube routine was used for the Most Probable Number Analysis (a statistical technique for assessing the approximate number of bacteria in a sample). The water sample is inoculated into several test tubes filled with nutrient broths according to the micro-organism that is going to be identified. Three sets of tests (Presumptive, Confirmed and Completed) were used to identify and count the number of a certain species of bacteria. A three or five tube series is made of decreasing volumes of this sample: 10 ml, 1 ml and 0.1 ml or any similar combination (100, 10 and 1; 1, 0.1 and 0.01; etc.). After the incubation (usually for 24 hours at a fixed temperature) the number of positive tubes (those that show bacterial growth or consequences of it)

are counted. With this number a MPN index per 100 ml is calculated or found on a table.

Subsequent Tests:

In order to gain insight into the comparative effectiveness of this simple water purification technique for one source of water with regard to other source a second set of tests was programmed. Water samples from two fountains near the University, which are presently in use, were analyzed at the same time.

At 10:00 hours, two samples each of the source waters were taken at two different locations. The first sample at each location was immediately incubated through the normal three test tube routine. The second sample was exposed to solar radiation in the transparent bottle (Aguardiente Cristal) placed over a white diffuse reflector. At the same time solar radiation measurements were also recorded.

In the afternoon, between 15:00 hours and 17:00 hours (depending on the intensity of solar radiation) the samples were fed into the incubating tubes and the integrated radiation measurement of the day's experiment was taken. In both cases results of the normal three test tube routine were analyzed by the Most Probable Number Analysis.

At the same time, integrated and instantaneous measurements of solar radiation were recorded.

FINDINGS OF THE INVESTIGATION

Initial Tests (see Tables 2, 3 and 4):

These tests were made on different days on individual water sources actually used by the local population. This selection was made in order to sample the actual conditions in which the water purification routine would operate, if found viable. Thus the results are not statistically comparable, nevertheless, they show, what would have been some typical daily results of this technique, scattered over space and time. The main outcomes of this part of the study are as follows:

i) Samples of ten out of eleven water sources used for drinking purposes, showed positive counts of coli bacteria and in some cases the water presently being used is highly contaminated.

ii) Results of the experiment definitely indicate that there was a reduction in the number of bacteria in the water samples exposed to sunshine. An increase in the total bacterial count was detected in only three out of 33 tests, while the number of total coliform bacteria did not increase in any of the tests and in just one case an increase in the fecal coli count was detected.

iii) One case each of 100% kill of total bacteria and total coliforms was detected while out of five positive initial counts of E. coli bacteria two cases of 100% kill were observed.

Subsequent Tests (see Tables 5, 6 and 7):

The secondary part of the tests was planned in order to correlate the amount of solar

radiation, under actual field conditions, with the survival rates for the same water source. However, due to extremely low intensity of solar radiation during the test period a very poor correlation was found between total radiation and the bacterial survival. Nevertheless, an inactivation trend for total and faecal coliforms was noted.

DISCUSSION AND CONCLUSIONS

In spite of a very unfavourable combination of parameters such as the lowest radiation averages in the country (and probably one of the lowest in the world, for this latitude); a high percentage of diffuse radiation component; waters contaminated by continuous washing of the coffee beans (which implies hydrolyzed proteins and carbodydrates) and by the disposal of domestic and other wastes etc., the solar water purification method shows a general tendency towards a reduction in the total bacterial count, the total coliform count and the fecal coliform count. However, only one contaminated sample was purified close to the national standards for water consumption.

Although the general objective was met, there is not enough statistical evidence to present relevant correlations between low radiation expositions and bacterial reduction that could lead to the physical determination of the lower radiation limits for a safe use of the technique under the climatic and contamination restrictions of this tropical environment. It is recommended that for a stable water source (in terms of contamination) a one year measurement of the disinfection capacity of solar radiation with the aim of determining the correlation between total radiation (preferably the UV fraction), and bacterial survival counts. From these experiments the lower limits for this simple technology could be determined. Controlled experiments in areas with similar environmental characteristics and water quality but better solar radiation availability may also provide more illuminating results.

TABLE 1 SITE DESCRIPTION FOR THE FIRST SET OF EXPERIMENTS IN PEREIRA (COLOMBIA).

Name	Source	Avg temp. (°C)	Socioeconomic level	Users
Danubio I	Gravity-fed tank from an open fountain	23	Low: Informal periurban settlement	190 fam.
Yarumal I	Gravity-fed bamboo and PVC pipe from open fountain	20	Low: Rural settlement	12 fam.
Yarumal II	Open creek settlement	20	Low: Rural	Not used.
San Vicente	Gravity-fed tank from an open fountain	25	Low-low: Informal settlement	150 fam.
Canceles I	Open Fountain	25	Low-interm: Periurban mini-farms	4 fam.
Canceles II	Open fountain	25	Low-interm: Periurban mini-farms	3 fam.
Canceles III	Open fountain	25	Low-interm: Periurban mini-farms	3 fam.
Canceles IV	Gravity-fed PVC pipe from open fountain	25	Low-interm: Rural school	180 pers.
Bosque I	Open fountain	28	Low-interm: Rural	7 fam.
Teneria	Open fountain and tank	28	Low-interm: Periurban	5 fam.
Dos Quebradas	Open fountain	25	Low-low: Informal urban settlement	4 fam.

TABLE 2 TOTAL BACTERIA COUNTS (PER 100 ml) DURING THE FIRST SET OF EXPERIMENTS.

	Initial	After 2 h	After 4 h	Variation (%)
Danubio I	7200	600	1800	-75.0
Yarumal I	4400	1900	24000	+445.5
Yarumal II	3000	3000	43000	+1333.3
San Vicente	1500	9000	5000	+233.3
Canceles I	43	10	0	-100.0
Canceles II	90	80	60	-33.3
Canceles III	670	850	110	-83.6
Canceles IV	170	140	280	+64.7
Bosque I	340	40	110	-67.6
Teneria	500	260	200	-60.0
Dos Quebradas	7600	6000	600	-92.1

TABLE 3 TOTAL COLIFORMS COUNTS (PER 100 ml) DURING THE FIRST SET OF EXPERIMENTS.

Source	Initial count	After 2 h	After 4 h	Variation (%)
Danubio I	9300	43	12	-83.9
Yarumal I	3900	430	750	-80.8
Yarumal II	150	93	93	-38.0
San Vicente	240	93	7	-97.1
Canceles I	1500	750	43	-97.1
Canceles II	430	230	93	-78.4
Canceles III	9300	2300	430	-95.4
Canceles IV	9300	43	230	-97.5
Bosque I	1500	430	0	-100.0
Teneria	430	230	430	0.0
Dos Quebradas	4300	4300	1500	-65.1

TABLE 4 FAECAL COLIFORM COUNT (PER 100 ml) DURING THE FIRST SET OF EXPERIMENTS.

Source	Initial count	After 2 h	After 4 h	Variation (%)
Danubio I	43	15	9	-79
Yarumal I	9.3	3.6	0	-100
Yarumal II	75	43	3	-96
San Vicente	0	0	0	-
Canceles I	0	0	0	-
Canceles II	0	7	0	-
Canceles III	0	0	0	-
Canceles IV	0	0	0	-
Bosque I	0	4	0	-
Teneria	2	9	27	+1250
Dos Quebradas	30	0	0	-100

TABLE 5 TOTAL BACTERIA COUNTS (PER 100 ml), ACCUMULATED RECEIVED RADIATION (Kcal-day/m^2) AND PERCENT OF BACTERIAL SURVIVAL DURING THE SECOND SET OF EXPERIMENTS IN PEREIRA (COLOMBIA).

Source	Initial count	Final count	Accumulated radiation	Bacterial survival (%)
Lorema	370	90	1230	24.3
Poblado	1100	100		9.1
Lorema	1400	100	2576	7.1
Poblado	4400	600		13.6
Lorema	900	100	1902	11.1
Poblada	7700	700		9.1
Lorema	290	10	1711	3.5
Poblado	2100	100		4.8
Lorema	370	10	1815	2.7
Poblado	37000	17000		45.9
Lorema	200	0	2813	0
Poblado	7000	300		4.3

TABLE 6 TOTAL COLIFORM COUNTS (PER 100 ml), ACCUMULATED RECEIVED RADIATION (Kcal-day/m^2) AND PERCENT OF BACTERIAL SURVIVAL DURING THE SECOND SET OF EXPERIMENTS IN PEREIRA (COLOMBIA).

Source	Initial count	Final count	Accumulated radiation	Bacterial survival (%)
Lorema	9300	1500	1230	16.1
Poblado	2300	960		41.7
Lorema	23000	15	2576	0.1
Poblado	21000	4		0.1
Lorema	9300	23	1902	0.3
Poblado	4300	4		0.1
Lorema	7500	9	1711	0.1
Poblado	2100	93		4.4
Lorema	23000	23	1815	0.1
Poblado	43000	930		2.2
Lorema	9300	23	2813	0.2
Poblado	230	0		0.0

TABLE 7 FAECAL COLIFORM COUNTS (PER 100 ml), ACCUMULATED RECEIVED RADIATION (Kcal-day/m^2) AND PERCENT OF BACTERIAL SURVIVAL DURING THE SECOND SET OF EXPERIMENTS IN PEREIRA (COLOMBIA).

Source	Initial count	Final count	Accumulated radiation	Bacterial survival (%)
Lorema	4	4	1230	100.0
Poblado	4	0		0.0
Lorema	4300	9	2576	0.2
Poblado	93	0		0.0
Lorema	2100	9	1902	0.4
Poblado	23	4		17.0
Lorema	9300	10	1711	0.1
Poblado	9	0		0.0
Lorema	7500	9	1815	0.1
Poblado	64	0		0.0
Lorema	2300	0	2813	0.0
Poblado	23	0		0.0

SOLAR WATER DISINFECTION: EXPERIENCES IN THAILAND

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ABSTRACT

Natural disinfection of rural water supply by solar irradiation has been investigated. Experiments were designed for evaluating the UV disinfection and rise-in-temperature disinfection laboratory models. Raw water from shallow wells and irrigation canals were used for experiments. The UV laboratory model was designed in order to study the effect of natural UV disinfection on the micro-organisms in the unit. While the rise-in-temperature disinfection model was designed in order to study the heat effect of solar radiation on disinfection. The specific UV model used did not show satisfactory results in disinfection. The number of micro-organisms were sometimes decreasing due to disinfection and sometimes increasing due to growth. Opaque material used for the container, inhibit UV exposure on the water volume. The temperature disinfection model shows significant success in faecal coliform inactivation. The model with a solar collector using copper tubes showed good disinfection results in that all faecal coliforms were inactivated in a detention time of 15 minutes during 11:00-15:00 hours of a clear day and provided temperatures above 60°C. The model with a solar collector using glass tubes showed some disinfection capabilities. Faecal coliforms could be totally inactivated with 20 to 40 minutes of detention time. The solar collector with galvanized steel conduits did not show any good disinfection results.

INTRODUCTION

"Disinfection" is a key word in water engineering to produce disease-free water for human consumption. The objective of disinfection is to obtain microbiologically clean water which should contain no pathogenic organisms and be free from biological forms that may be harmful to human health or aesthetically objectionable. There are many methods of disinfection available and being practically used in water works all over the world. The most popular and oldest disinfection method used in water works is chlorination. Apart from chlorination, other methods of disinfection were also introduced such as the use of ozone, ultraviolet radiation etc. None of these methods are appropriate for rural water supply because of their complexity and high cost. Therefore, alternative methods of disinfecting drinking water should be available for rural areas.

The sun is the ultimate origin of most of the energy presently available on earth. Solar disinfection could be one of the feasible alternative disinfection methods for obtaining potable water. Disinfection by solar irradiation occurs in solar still due to a rise in temperature and/or UV irradiation [1]. Recent reports from Israel [2] and Lebanon [3] stated the possibility of using sunlight to disinfect water. Natural ultraviolet rays, especially those in the wavelength range of 300-400 nm, can transmit through the earth's atmosphere. This radiation could disinfect water at the surface of

lakes and reservoirs. Apart from the UV component, the visible and infrared components also penetrate through the atmosphere. Cold water in a container exposed to the sun, undergoes a rise in temperature. With the water temperature above 60°C for a certain period of time, all E. coli and other pathogens in the water can then be inactivated. In view of the above, a project was undertaken at Chiang Mai University to study the effect of solar irradiation on disinfection of drinking water in rural areas of Thailand. This paper presents some of the findings of the above project.

PROCEDURES

Two models of the laboratory scale experiments were selected for the study. Type A model was a UV disinfection model, and type B model was a rise-in-temperature disinfection model.

Type A Model (UV Disinfection Model)

Figure 1 shows the design of the prototype experimental unit of the UV disinfection model. The unit consists of a water container with 20 circulation chords. The water container was built with PVC sheet with rubber circulation chords connected between the upper and lower part of the container. Rubber chords were made of polyethylene tube 25 mm in diameter. They were painted black to absorb solar radiation. When the designed units are put into sunlight, water at the surface of the containers is exposed to solar radiation. After a certain period of time, the water in the black chord is heated. Since the water in the chords has a higher temperature than in the containers, water in the chords rises up to the surface of the containers. This creates natural circulation within the containers. Three different sizes of UV disinfection containers were constructed with capacities of 50 litres (S), 100 litres (M) and 200 litres (L).

Type B Model (A Rise-in-Temperature Disinfection Model)

Each of the design units consists of a uniform gravity feeding tank, a simple flat plate solar collector and a receiving container. Schematic diagrams of the three units are shown in Figure 2. A uniform gravity feeding tank was constructed using two water containers. The upper container was a storage container with a capacity of 150 litres. The lower container was a constant head container with a similar capacity of 150 litres. Water was placed into the storage container and flowed to the constant head container through a level control valve. The control valve keeps water level in the second container constant. Water flows from the constant head container through an ordinary tap valve which adjusts the flow rate. Water flows through the tubes of the solar collector with a constant flow rate, and is finally collected in an earthenware jar used as a receiving container.

Three simple solar collectors were constructed for the experiments (Figure 3). The first solar collector was constructed using a copper tube 19 meters long with a diameter of 9 mm. The tube was bent in a serpentine curve bonded to a steel absorber plate by metal strings. The absorber plate has dimensions of 1.22 x 1.22 meters. Glass fibre insulation was used underneath the absorber plate. The absorber plate was painted black to absorb maximum solar radiation. The solar collector was then covered by a glass pane. The second solar collector was constructed using glass tubes with a diameter of 10 mm. and a length of 1.16 meters each. Twenty glass tubes were supported

by a wooden frame on a steel absorber similar to the absorber plate described above. It should be mentioned that since, in this case, the glass tubes were not in contact with the steel absorber plate, solar radiation intercepted directly by the glass tubes was mainly responsible for an increase in the water temperature. The individual glass tubes were connected at their ends by silicon rubber tubes to form a continuous serpentine configuration. The absorber plate was painted black. The third solar collector was constructed using galvanized steel conduit pipes of 12 mm diameter. Seven steel pipes, each 1.75 m long, were connected by two 90x bends at each end to form a serpentine configuration. The steel pipes were laid on top of a wooden board with a thickness of 3.5 cm. The pipes were attached to the wooden board by steel rings. The steel pipes were was also painted black to absorb maximum solar radiation.

Experiments on Type A Model

Two levels of turbidity were considered to study the effect of turbidity on disinfection. The experiments were performed under two conditions, five tests on the units with plastic covers and four experiments without plastic covers. Raw water from shallow wells and irrigation canals with different turbidity levels was used for experiments, which were carried out during March and April 1985 on days with clear sky. Turbidity and pH of raw water were measured at the beginning of the test by using turbidity meter Hach model 2100A, and pH meter Radiometer model PHM 62, respectively. Samples were taken for analysis at the beginning and at the end of the experiment on the day the experiments were conducted. They were analysed for Most Probable Number (MPN) and total plate count using standard methods suggested by the American Public Health Association (APHA) [4]. The temperature of the water in the containers was measured every hour using a mercury thermometer.

Experiments on Type B Model

The experiments were performed by using water which was moderately polluted as well as by using water contaminated with domestic waste from a waste treatment plant. The range of feacal coliform of natural tested water was in the order of 15 1007 N/100 ml, while the range of faecal coliform of waste added tested water was in the order of 589-2286 N/100 ml. For each type of water the effect of three different detention times was studied and these experiments were conducted with each prototype unit. The water temperature was recorded at the inlet point, the outlet point and in the storage jar, by using a data-logger Minitrend 205. Raw and treated water samples were taken every hour for bacteriological analysis. Total coliform, faecal coliform and standard plate count were measured using standard methods [4]. Turbidity and pH were measured at the beginning of the test. The water flow rate was measured by using a stop-watch and a graduated cylinder.

RESULTS AND DISCUSSION

UV Disinfection Laboratory Model

The results of the experiments are tabulated in Table 1. The first five tests were performed with clear plastic covers over the units. The latter four tests were performed without a cover. The results show that the size of the containers definitely affects the disinfection capability of the unit with 99% confidence limit. The plastic cover affects disinfection with a 95% confidence limit. The results show that the

larger the unit used, the higher the rate of bacterial inactivation. Water turbidity also affects the phenomenon of inactivation. With higher turbidity of raw water, the bacterial inactivation fluctuates. It may therefore be stated that with larger surface area of the models, and with relatively non-turbid water, better disinfection of water can be achieved. The UV disinfection model does not appear to be effective when used with turbid waters. The plastic cover seems to reduce the disinfection effect in the large sized units. This is because with plastic covers or any other transparent materials the passage of natural UV is reduced. Besides, after a certain exposure time, a number of water droplets are deposited on the inside surface of the covers due to condensation of water vapour, which inhibit the transmission of solar radiation.

During the exposure period both the disinfection and reproduction of bacteria is taking place. In the results obtained from the experiments conducted on the prototype models, a variation in the number of bacteria was observed. At certain times, the bacteria population was found to decrease while at several other occasions an increase in population was noticed. With exposure time between 5.5 and 6.5 hours, the temperature of the water in the models increased by 6 to 12°C depending on weather conditions. Final temperatures in the three units were in the range of between 35 to 38°C. The pattern of decrease and increase in the population of micro-organisms in the units, was not clear. Apparently disinfection occurred and at the same time micro-organisms also happened to grow. This is because the temperature range between 35 to 38°C may be a very good environment for their growth. If the rate of disinfection was greater than the growth rate of the bacteria, the result would show a decrease in the population of micro-organisms. On the other hand if the rate of disinfection was lower than growth rate, then the result would show an increased population of micro-organisms in the water.

The results also show that the population of micro-organisms at the upper layer and bottom layer of the units are different. About 5 tests out of 27 tests show the same range (differing approximately by 10 units of MPN) of micro-organisms, in term of MPN, between upper layer and bottom layer of the unit. This means that, contrary to the expectations, the natural circulation through the chords was not very effective.

Rise in Temperature Disinfection Model

Variation of water temperature in Model B

Three different solar collectors utilized solar radiation with different collection efficiencies. Figure 4 shows average temperature of the water passing through the solar collector with copper tubes during the first six runs of the experiment. The daily average temperature is indicated with standard deviation in this figure. Average temperature of the water increases with exposure time. Figure 5 shows average temperature of the water passing through the three solar collectors. The variation in the average temperature of the water with exposure time is not very clear. This may be because of the difference in solar radiation intensity on different days of the experiment. In the case of the solar collector with copper tubes, a maximum temperature of 70.4°C was obtained on 9 April, 1986 between 13:00-14:00 hr. The results show that about 70% of the time, of the whole experiment, water temperature from the copper tubes exceeded 55°C and for more than 35% of the time it exceeded 60°C. This high temperature range was observed mainly between 11:00-15:00 hr. on the days the experiments were conducted.

In the case of the solar collector with glass tubes, the average temperature of the water varied between 35-51°C. The water temperature was found to increase with exposure time. The maximum temperature ever recorded in this case was 52.4°C on 25 March 1986 at 13:00 hours. During the experiments, about 54% of the time, water temperature was higher than 45°C. However, temperatures higher than 60°C were not achieved.

In the case of the solar collector with steel conduits, the average temperature of the water in the unit was between 45 and 55°C. The water temperature was found to increase with exposure time in this case as well. The maximum water temperature of 58.8°C was obtained at 14:00 hours on 9 April 1986. About 53% of the time water temperature was higher than 50°C. Similar to the case of the collector with glass tubes water temperature exceeding 60x was not achieved.

Disinfection of water in Model B

Tables 2, 3, and 4 show the number of times (%) that faecal coliforms were completely inactivated by the solar collectors with copper tubes, glass tubes and the steel conduit, respectively. In the case of the solar collector with copper tubes, water temperature higher than 60°C ensured 100% faecal coliform inactivation of natural raw water. With the temperature range between 51 to 60°C , about 50 to 67% of the time, all faecal coliforms could be inactivated. For temperatures below 50°C, only 16% of the time complete inactivation of faecal coliforms could be achieved. However, the degree of contamination also affects the results. When waste water was added into the samples, only 37.5 to 80% of the time that all faecal coliform could be inactivated at temperatures higher than 60°C. Similarly, for waste water added samples, in the temperature range 41 to 50°C, in only 33% of the samples the faecal coliforms were inactivated. In the case of solar collectors using glass tubes, faecal coliform could be completely inactivated only at temperatures higher than 50°C and with a long detention time of 22 to 40 minutes. But when waste water was added, not a single measurement in the experiments indicated safe drinking water quality. A very poor inactivation of faecal coliforms was also observed for detention times less than 20 minutes (all faecal coliforms were inactivated only 9 to 28% of the time). Results from the solar collector using steel conduits were similar to those obtained for the solar collector with glass tubes.

In the case of the solar collector with copper tubes, the detention time above 15 minutes was found to ensure high temperature between 11:00-15:00 hours of the day and complete disinfection was achieved. But with the solar collector using glass tubes, complete disinfection was obtained only with the exposure time over 20 minutes, as the temperature was below 60°C. The solar collector using steel conduit did not show complete disinfection, no matter how long the exposure time was.

It seems that the initial amount of micro-organisms does affect the degree of disinfection. When raw waste water from treatment plant was added into the experimental samples, complete disinfection was not satisfactorily achieved.

The water used in the experiment on Model B was mainly from shallow wells. Turbidity of the experimental water ranged between 1-10 NTU. The results did not show the clear effect of turbidity on the disinfection process. It seems that with the turbidity ranging between 1-10 NTU, disinfection does not depend on turbidity of the water. NTU (Nephelometric Turbidity Unit) is the unit used for expressing level of turbidity

in water. The measuring method is based on a comparison of the intensity of light scattered by the sample under defined conditions with the intensity of light scattered by a standard reference suspension under similar conditions. Formazine polymer is used as the reference turbidity standard suspension.

CONCLUSIONS

The experimental UV model did not show a complete disinfection of water. The number of micro-organisms was sometimes decreasing due to disinfection and sometimes increasing due to growth of micro-organisms. Proper circulation of water through the chords could not be achieved. Opaque material used for the container, inhibits UV exposure on water body. The water surface exposed to natural UV is perhaps too small for enhancing disinfection. The use of transparent materials for the container or an increase in the surface area of the container may be considered to improve the performance of this model.

The temperature disinfection model showed better performance than the UV disinfection model. The three simple solar collectors developed could inactivate faecal coliforms to a certain degree. The model using solar collector with copper tubes showed best results in disinfection. Required temperature of about 60°C with a detention time of 15 minutes ensured complete disinfection. The model using the solar collector with glass tubes showed some disinfection capabilities. Faecal coliforms could be completely inactivated only with high detention times (20-40 minutes) with this model. The model using the solar collector with steel conduits did not show satisfactory results in disinfection. In this case water temperature never reached 60°C even with the detention times of more than 20 minutes.

RECOMMENDATIONS

The models using solar collector with copper tubes and glass tubes may be applied and modified for real practical use. With solenoid valve or any other automatic valve, water temperatures above 60°C may be obtained under any sun conditions and it could be used during a longer period of time besides 11:00 to 15:00 hours and a constant head feeding system would not be necessary.

ACKNOWLEDGEMENTS

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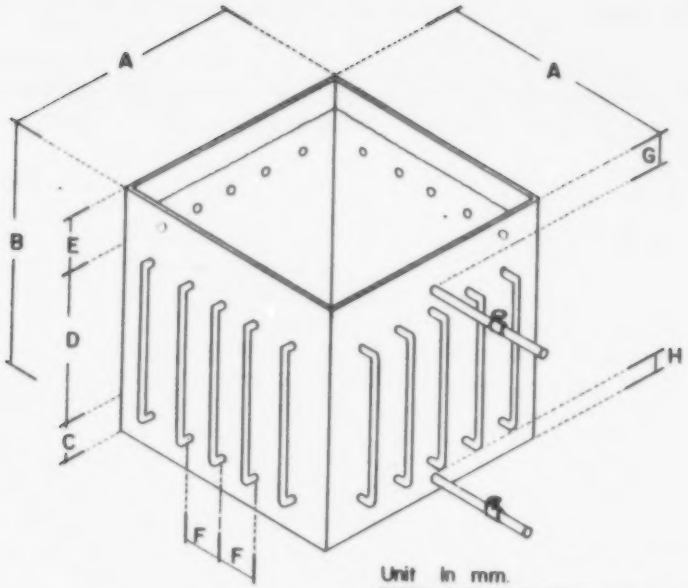


Unit in mm.

	A	B	C	D	E	F	G	H
L	580	580	70	405	105	100	55	20
M	450	450	70	290	90	80	40	20
S	365	365	70	180	105	65	65	20

Figure 1 UV disinfection unit for experiment

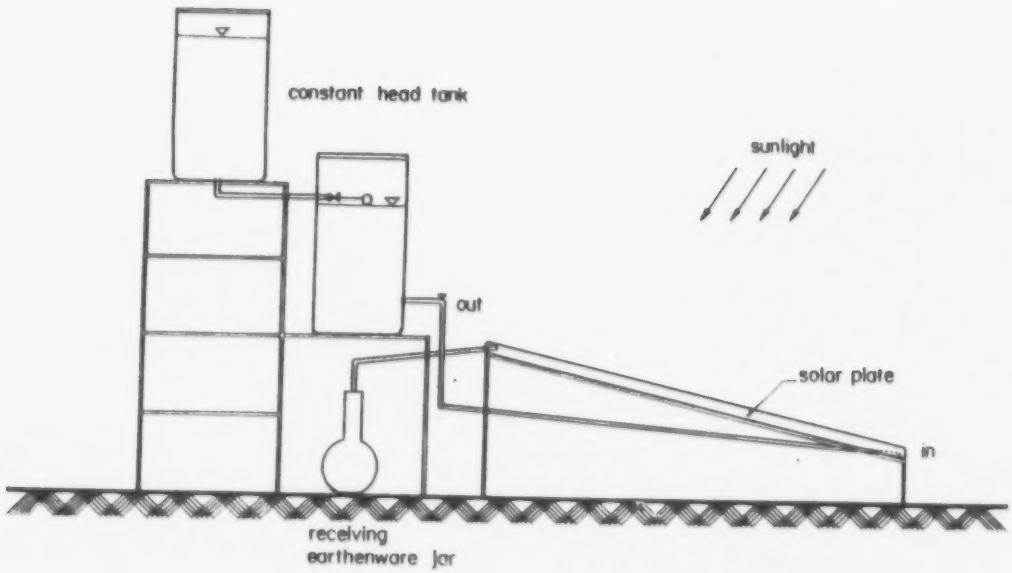
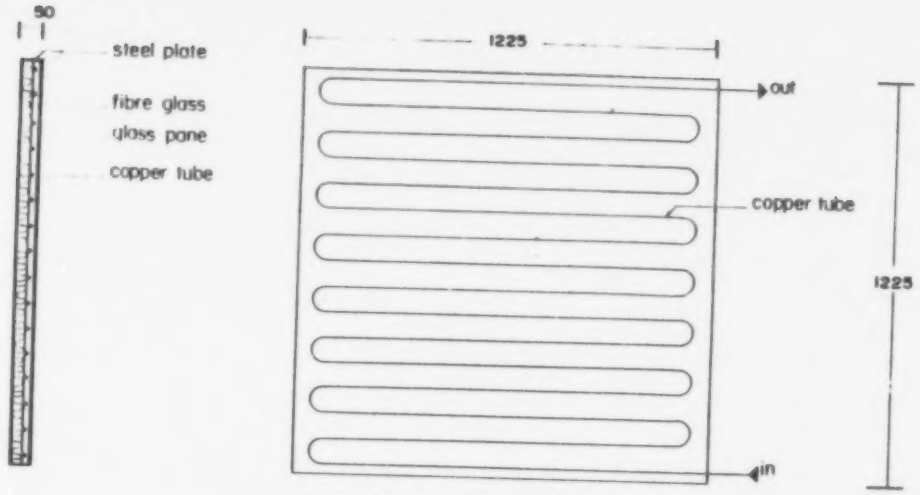
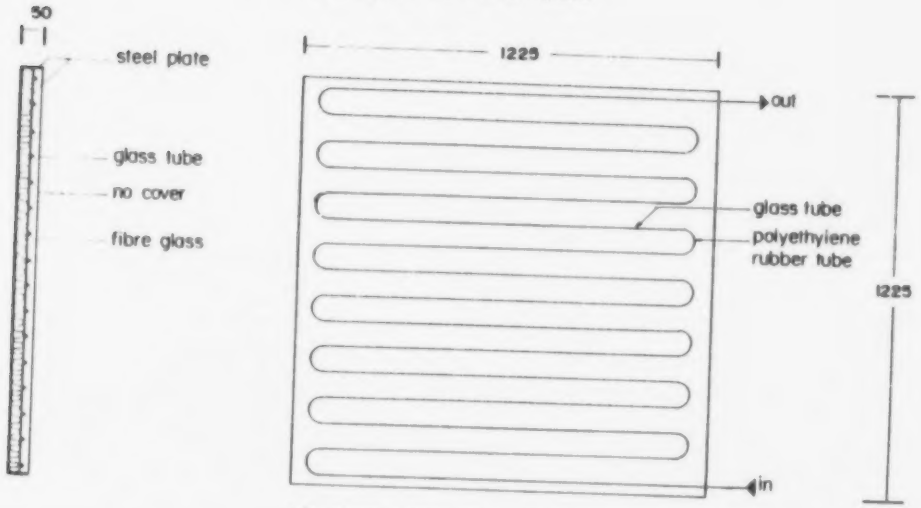


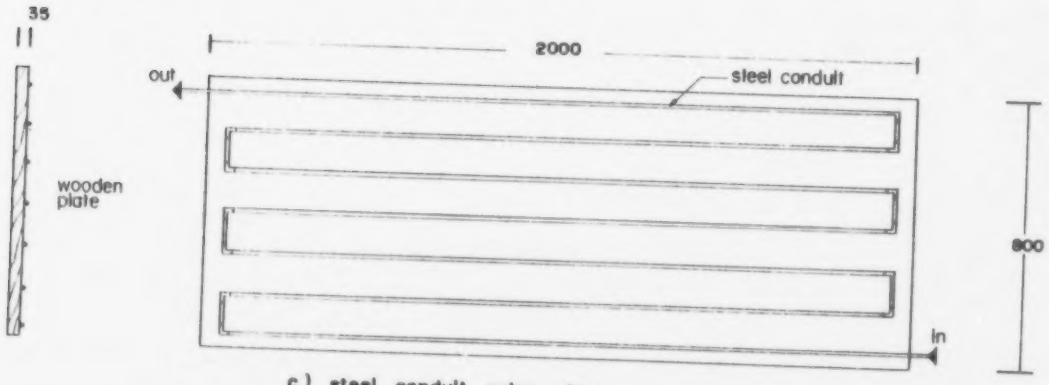
Figure 2 A Rise - In - Temperature Disinfection Model



a) copper tube solar plate



b) glass tube solar plate



c) steel condult solar plate

Figure 3 Solar plates

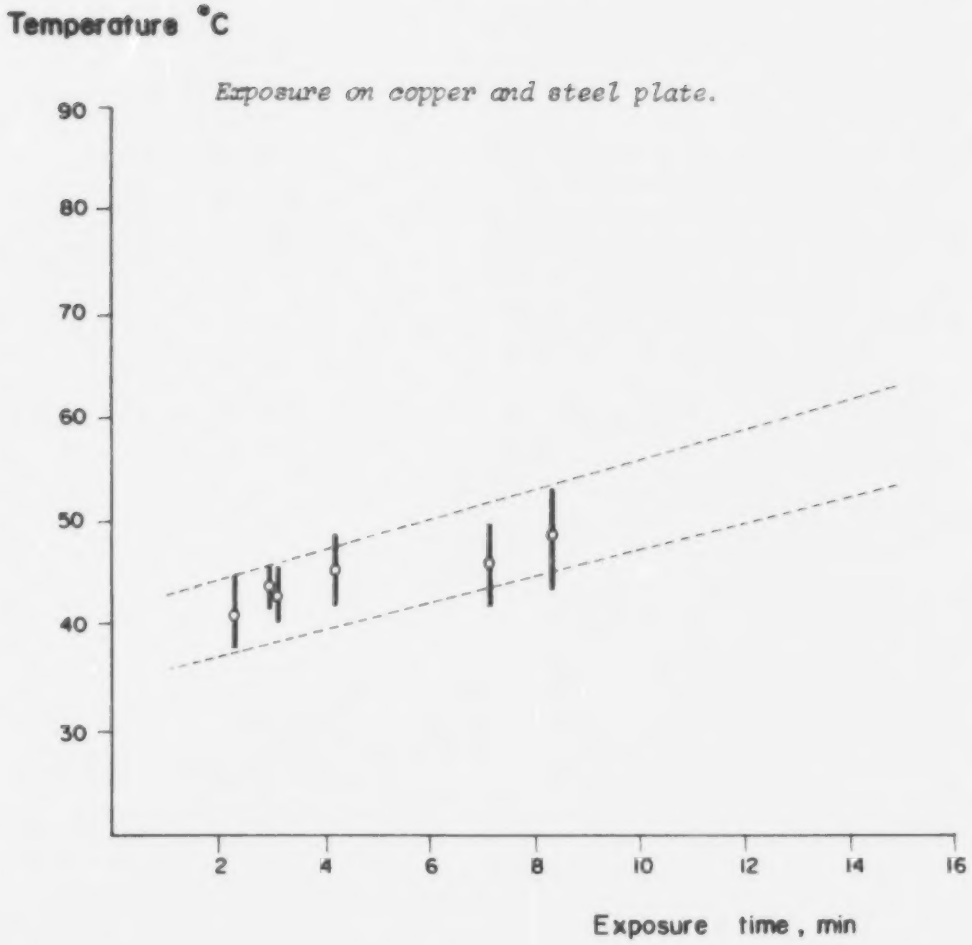


Figure 4 Relationship between exposure time and average temperature

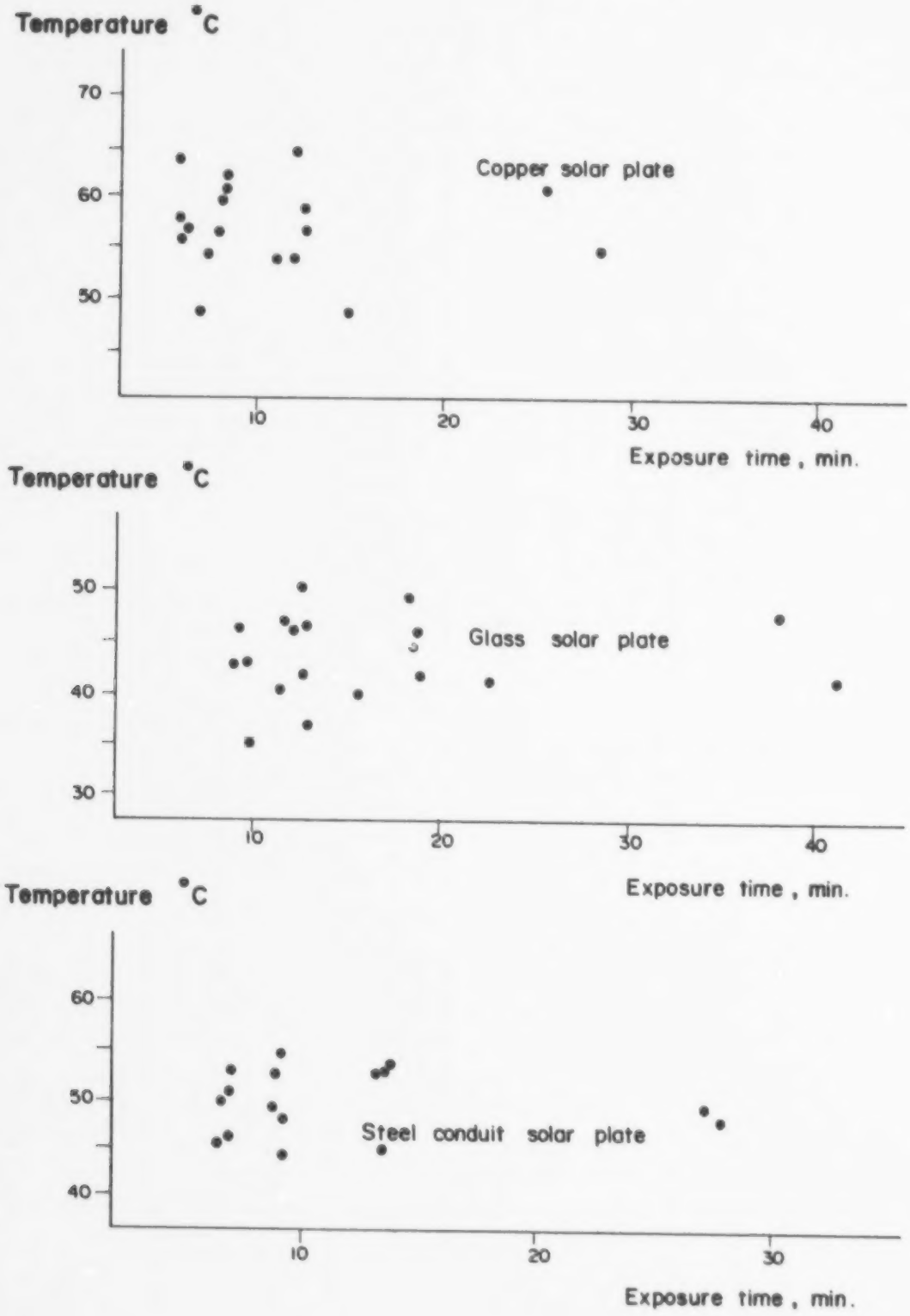


Figure 5 Relationship between average temperature and exposure time of the three solar plates

Table 1(a) Results from UV disinfection unit.

Run no.		Turbidity NTU	Expose time, hr	Increase of temp	MPN / % change			Plate Count / % change		
					Initial	Final upper	Final lower	Initial	Final up	Final down
1	L	4	5.5	11	140	170 / + 21.4	21 / - 85.0			
	M	3.8	5.5	10	49	140 / + 185.7	110 / + 124.5			
	S	4	5.5	10.5	79	- / -	920 / + 1,064.5.			
2	L	21	6.5	11	920	130 / -85.8	110 / - 88.0			
	M	19	6.5	11.5	31	140 / + 351.6	33 / + 6.5			
	S	14	6.5	12.5	540	49 / - 90.9	11 / - 97.9			
3	L	12	6.5	9	130	25 / - 80.7	80 / - 38.5			
	M	12	6.5	9	110	130 / + 18.2	50 / - 54.5			
	S	12	6.5	10	120	50 / - 58.3	50 / - 58.3			

Table 1(b) Results from UV disinfection unit.

Run no.		Turbidity NTU	Expose time, hr	Increase of temp	MPN / % change			Plate Count / % change		
					Initial	Final upper	Final lower	Initial	Final up	Final down
4	L	5.4	6.5	9	225	25 / - 88.8	80 / - 64.4	17,200	15,600 / - 9.3	3,900 / - 77.3
	M	5	6.5	10	225	20 / - 91.1	50 / - 77.7	37,000	3,400 / - 90.8	4,600 / - 87.5
	S	7.7	6.5	10.5	50	25 / - 50	50 / 0	46,000	26,000 / - 43.5	14,000 / - 69.6
5	L	5.4	6.5	7	25	6.8 / - 72.8	8 / - 68.0	13,000	1,250 / - 90.5	8,600 / - 33.8
	M	5.3	6.5	7	17	2.5 / - 47.0	13 / - 23.5	10,800	1,080 / - 90	6,900 / - 36.1
	S	5.4	6.5	8.5	17	11 / - 35.2	13 / - 22.2	14,200	3,000 / - 78.8	1,820 / - 87.2
6	L	26	6.0	9	350	550 / + 57.1	275 / - 21.4	28,200	50,000 / + 77.3	20,200 / - 28.0
	M	24	6.0	10	170	250 / + 47.0	50 / - 70.5	17,200	28,900 / + 68.0	26,200 / + 52.3
	S	23	6.0	10.5	250	350 / + 40.0	250 / 0	36,000	21,000 / - 41.6	29,000 / - 19.4

Table 1(c) Resultsfrom UV disinfection unit.

Run no.		Turbidity NTU	Expose time, hr	Increase of temp	MPN / %change			Plate Count / % change		
					Initial	Final upper	Final lower	Initial	Final up	Final down
7	L	23	6.5	7	350	110 / - 68.6	250 / - 28.5	30,000	24,000 / - 20.0	31,900 / + 6.3
	M	21	6.5	8	140	130 / - 7.1	350 / + 150	51,000	40,000 / - 21.6	40,000 / - 21.6
	S	18	6.5	8.5	900	170 / - 81.1	170 / - 81.	22,100	21,200 / - 4.1	24,000 / + 8.6
8	L	18	6.5	8	80	13 / - 83.7	50 / - 37.5	13,000	16,800 / + 13.8	10,400 / - 20.0
	M	12	6.5	9	110	13 / - 88.2	17 / - 84.5	20,200	14,000 / - 30.7	10,400 / - 48.5
	S	17	6.5	8	130	35 / - 73.0	25 / - 80.7	14,400	14,400 / 0	18,000 / + 25.0
9	L	17	5.5	5.5	80	6.8 / - 91.5	80 / 0	14,400	18,400 / + 27.8	24,000 / + 66.7
	M	14	5.5	6.8	130	45 / - 65.4	17 / - 86.9	12,400	16,000 / + 29.0	23,200 / + 87.1
	S	16	5.5	7	80	20 / - 17.5	20 / - 75.0	20,800	38,000 / + 82.7	25,000 / + 20.2

Table 2 Percent of time that Fecal coliform were completely removed by copper solar plate

Detention time (min)	Raw water	Temperature °C		% of time that all Fecal coliform were removed		
		Range	Average	at temp > 60°C	at temp 51-60°C	at temp 41-50°C
25-28	Natural	42.0-59.6	54.3±7.2	-	67%	0%
	Added waste	52.0-66.8	60.8±4.8	80%	0%	-
12-15	Natural	47.5-68.1	55.9±7.1	100%	65%	85%
	Added waste	42.0-56.0	50.0±4.7	-	0%	33%
6-8	Natural	35.8-67.5	56.7±7.4	100%	50%	16%
	Added waste	45.0-70.4	57.4±6.9	37.5%	15.4%	=0%

Table 3 Percent of time that Fecal coliform were completely removed by glass tube solar plate

Detention time (min)	Raw water	Temperature °C		% of time that Fecal coliform were removed		
		Range	Average	at temp > 50°C	at temp 41-50°C	at temp < 40°C
22-40 min	Natural	29.2-50.3	43.4±5.1	100%	54.5%	50%
	Added waste	38.3-51.7	47.8±4.3	0%	0%	0%
12-18 min	Natural	31.2-35.3	45.0±4.6	15%	14%	9%
	Added waste	32.7-45.6	40.7±4.2	-	0%	0%
9-11	Natural			-	11%	28%
	Added waste	39.0-48.6	43.1±4.1	-	0%	0%

Table 4 . Percent of time that Fecal coliform were completely removed by steel conduit solar plate

Detention time (min)	Raw water	Temperature °C		% of time that all Fecal coliform were removed		
		Range	Average	50-59°C	< 50°C	
27-28	Natural	45.9-57.3	49.8±3.0	33%	33%	
	Added waste	42.3-54.4	49.4±4.2	0%	0%	
13-14	Natural	40.9-58.2	52.2±1.4	21%	0%	
	Added waste	40.0-49.0	45.3±3.7	-	14%	
6-9	Natural	35.5-58.0	49.4±3.0	42%	5%	
	Added waste	39.2-50.8	48.5±3.2	14%	0%	

SOLAR DISINFECTION OF WATER FOR RURAL COMMUNITIES

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ABSTRACT

Surveys on water sources and use, as well as on the availability of containers in rural areas were conducted.

Naturally and artificially contaminated water samples were exposed to solar radiation in different containers, varying in material, colour and shape, and their bacteriological load was tested as a function of time of solar exposure. The optical properties of the containers were also studied, in order to determine the most suitable type of container, which will serve for the solar disinfection of water. The most lethal region of the solar spectrum, responsible for the germicidal effect of bacteria contaminating the water was also studied.

It was found that contaminated water becomes perfectly fit for human consumption after being exposed to sunrays for 2 to 4 hours depending on the type, shape and colour of the container. The most lethal range of the spectrum for the germicidal effect was that in the near UV region (350-500 nm).

INTRODUCTION

Water is essential for life. But water contaminated with disease causing organisms can be just as deadly as no water at all. In rural areas of the developing countries, most people have no access to a safe water supply nor adequate sanitation facilities. Many household wastes, agricultural wastes, community refuse and sewage are disposed directly into water bodies used for drinking, bathing, laundry and food preparation (Okoronkwo and Odeyemi, 1984; Petters and Odeyemi, 1985). As a matter of fact, 80% of sickness in developing countries is caused by water-borne and water-washed diseases, 60% of whom are children (Anon, 1986). In Egypt, one out of ten newborn children is destined to pass away before reaching the age of four, because of these diseases (Khalil, 1981).

An examination of water quality is basically a determination of the organisms as well as the mineral and organic compounds contained in the water. However, the most important parameter of drinking water quality is its bacteriological quality, i.e. its content of bacteria and viruses (Feachem et al, 1980). It is not practicable to test the water for all organisms that it might possibly contain. Instead, the water is examined for specific types of bacteria, which originate, in large numbers, from human and animal excreta and whose presence in the water is indicative of faecal contamination. Biological pollution of the water through faecal contamination is a basic cause of morbidity due to water-borne diseases which rank first among all other diseases in developing countries (Okoronkwo and Odeyemi, 1984).

In 1979, a pertinent study on the safety of water supplies in rural communities and the rampant enteric diseases was launched by Prof. Aftim Acra and his team at the Faculty of Health Sciences, the American University of Beirut (AUB). It was found that exposure of drinking water in a transparent container for a few hours to solar radiation would kill enteric bacteria in the water and make it fit for human consumption.

Under the United Nations University Contract No. ICA 85/143, the American University in Cairo (AUC) in cooperation with the Faculty of Veterinary Medicine, Cairo University, have participated in the Mini-Research Project MRP-6D on solar disinfection of water. Similar research projects have been executed in five other countries, namely Colombia, Peru, India, Sri Lanka and Canada. They all have been coordinated by the Brace Research Institute the INRESA Secretariat and sponsored by the United Nations University. The Mini-Research Project in Egypt aimed at assessing the feasibility of solar disinfection of Nile and underground water for drinking purposes that would satisfy the needs of an individual or a family in rural communities of Egypt. Modern "rediscovery" of this ancient method could save millions of lives in the rural communities of developing countries, where sunshine is available and the quality of the water supply is uncertain.

METHODOLOGY AND EXPERIMENTAL WORK

A survey was done in the Egyptian village Basaisa (Arafa, 1985), in terms of water sources and their bacteriological content. Water samples, taken from the most contaminated sources in the village, were exposed to sunrays for a period of five hours, and its bacterial content was measured every hour using the agar-plate method (Gerhardt, 1981) to detect the effect of solar radiation on it. The same was done under different radiation conditions (sunlight, room-lighting, dark).

Water disinfection was also, studied by using artificially contaminated water and artificial light source (tungsten lamp). Furthermore, the effect of the shape, volume and colour of the containers was studied. A survey was done in the Egyptian industrial market, in terms of local bottle manufacture. Ten samples were selected varying in material, shape and size. Electron Spin Resonance and Optical Absorption spectra of the ten samples were studied, in order to identify the bottle materials and the range of the solar radiation spectrum responsible for the bactericidal effect.

Finally, the applicability of this method of disinfection was tested on water samples taken from different sites along the river Nile.

RESULTS AND DISCUSSION

The fate of bacteria in water when being exposed to solar radiation for a period of time of five hours (from 08:30 hours to 13:30 hours) is illustrated in Figure 1. Diminution of the bacterial load occurs not only under direct solar radiation, but also under normal conditions of room-lighting as well as in complete darkness. However, the rate of their destruction differs according to lighting conditions, as illustrated in Figure 2 (Cotis, 1986).

Upon exposure of contaminated water to artificial radiation (tungsten lamp), the results came up similar to those obtained by exposing the water to direct solar

radiation. When the incident artificial radiation was filtered, so as to allow only certain wavelengths to be incident on the water sample, the bacterial diminution varied. These experiments showed that the near ultraviolet region (350 to 500 nm) is the most lethal region of the spectrum responsible for the germicidal action. The same was confirmed by exposing water to direct sunlight in coloured containers, as shown in Figure 3, the colour of each container depends on the colorant or impurity element, present in the bottle material (Cotis, 1986).

Artificially infected water with E. coli, Staphylococcus, Pseudomonas aeruginosa and Klebsiella pneumoniae, exhibited similar results when exposed to direct sunrays and room lighting.

Solar disinfected water was re-tested after one week storage in room conditions, as well as in complete darkness, and it was found pure.

SUMMARY AND CONCLUSIONS

The feasibility of the water disinfection by exposure to solar radiation was found to depend on three factors: the container used; the energy of the radiation transmitted through the container; the type of micro-organism present in the water.

The results indicate that although the intensity of the light transmitted to the water was the same for containers which transmit light in the near UV region, and those in the near IR region, their bactericidal effects were totally different. The highest degree of decontamination was achieved by containers transmitting in the near UV region of the spectrum. This leads to the conclusion that the bactericidal effect is accounted for by the wavelength, hence the energy, and not the intensity of the transmitted radiation. The most lethal range of the spectrum responsible for the germicidal effect was found to be the near UV (350 to 500 nm). The rise in the water temperature did not seem to play as an active role in the water decontamination process as the sunlight (Figure 4).

Regions having about 300 sunny days with clear skies per year, like Egypt, are naturally best suited for the utilization of solar energy for the disinfection of drinking water, as well as other applications. Cloud formation does not present serious problems throughout the greater part of the year. Clouds reduce the intensity of direct sunlight by scattering the sunrays, producing diffuse daylight. Diffuse daylight can exhibit bactericidal action, but at a slower rate. Therefore, during cloudy days it will be necessary to prolong the exposure period.

Further research work is needed in order to study the feasibility of the method on other micro-organisms specially on the Bilharzia, Cercaria and Cholera vibrio present in water, with the hope that it will serve as a useful guide for primary health care workers involved in the control of water-borne diseases.

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TABLE 1 RESULTS OBTAINED FROM THE SURVEY OF WATER RESOURCES IN THE VILLAGE OF BASAISA, EGYPT.

Source No.	Depth (m)	Bacterial content (ml)	Preference for use
2 Well	31	40×10^4	It is used by six neighbouring communities for all purposes.
6 Well	16	5.5×10^4	Used by 3/4 of the village for all purposes
8 Well	33	980×10^4	Used by 1/5 of the village for all purposes
9 Well	17	22×10^4	Used by most of the animals of the village due to its location in the fields
12 Well	32	2.1×10^4	The mosque well, used by all people
A Canal	0.5	30×10^4	Used by women for washing clothes and utensils, and by animals for drinking
B Stream	0.5	95×10^4	Similar to source A
C Stream	2.0	1.0×10^4	Used by men for swimming

TABLE 2 TOTAL BACTERIAL COUNT AND THE COLIFORM TITRE IN WATER SAMPLES COLLECTED FROM VARIOUS LOCALITIES IN THE NILE DELTA, EGYPT.

No.	Location	Total bacterial count	Coliform titre	Remarks
1	Well, Menia El-Kamh	190×10^7	10^3	
2	Public source, Menia El-Kamh	190×10^7	10^2	
3	Public source	185×10^7	10^3	Low total, high coliform
4	Well, Om Ramad	300×10^7	10^2	
5	Well, Taieba	350×10^7	10^1	Lowest coliform, high total
6	Stream, Teiba	200×10^7		

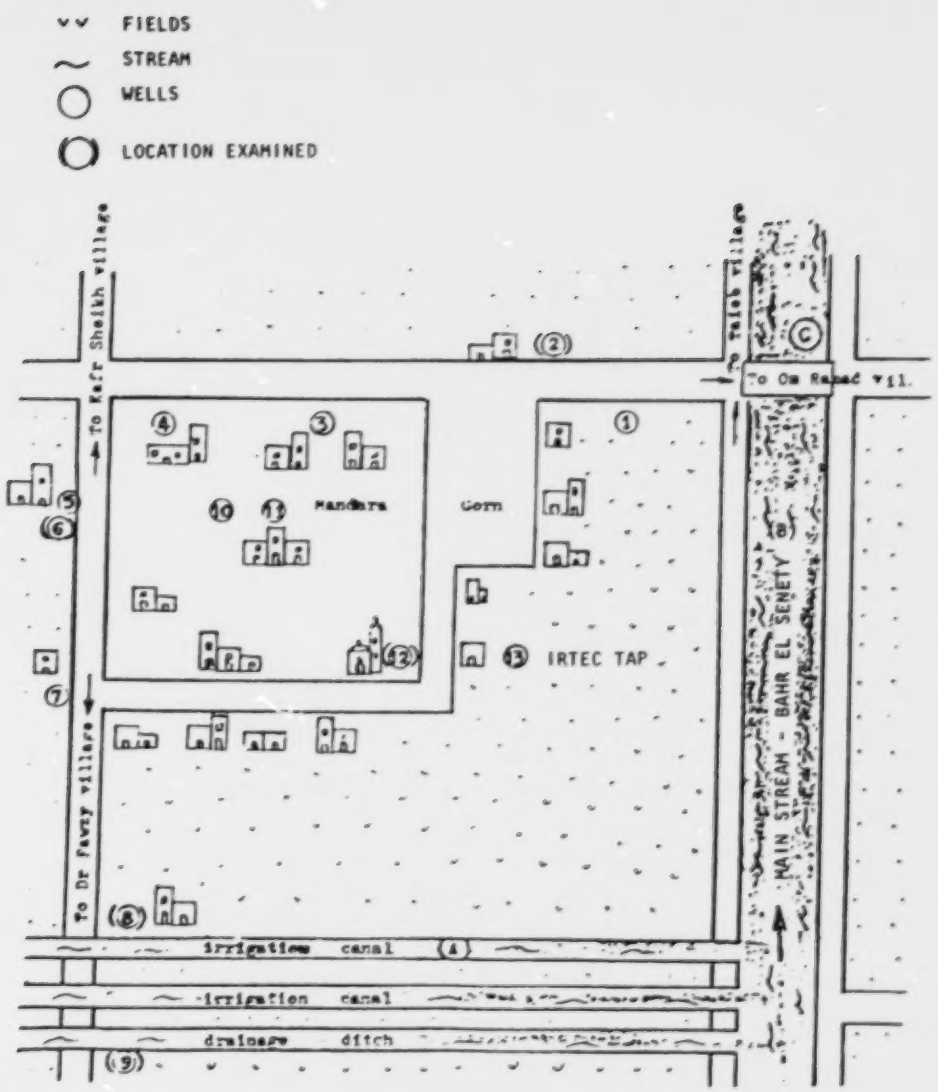

FIGURE 1. LOCATIONS EXAMINED FOR WATER CONTAMINATION IN THE VILLAGE OF BASAISA, 15 KM N.W. OF ZAGAZIG, EL-SHARKIYA GOVERNORATE, EGYPT

figure 2

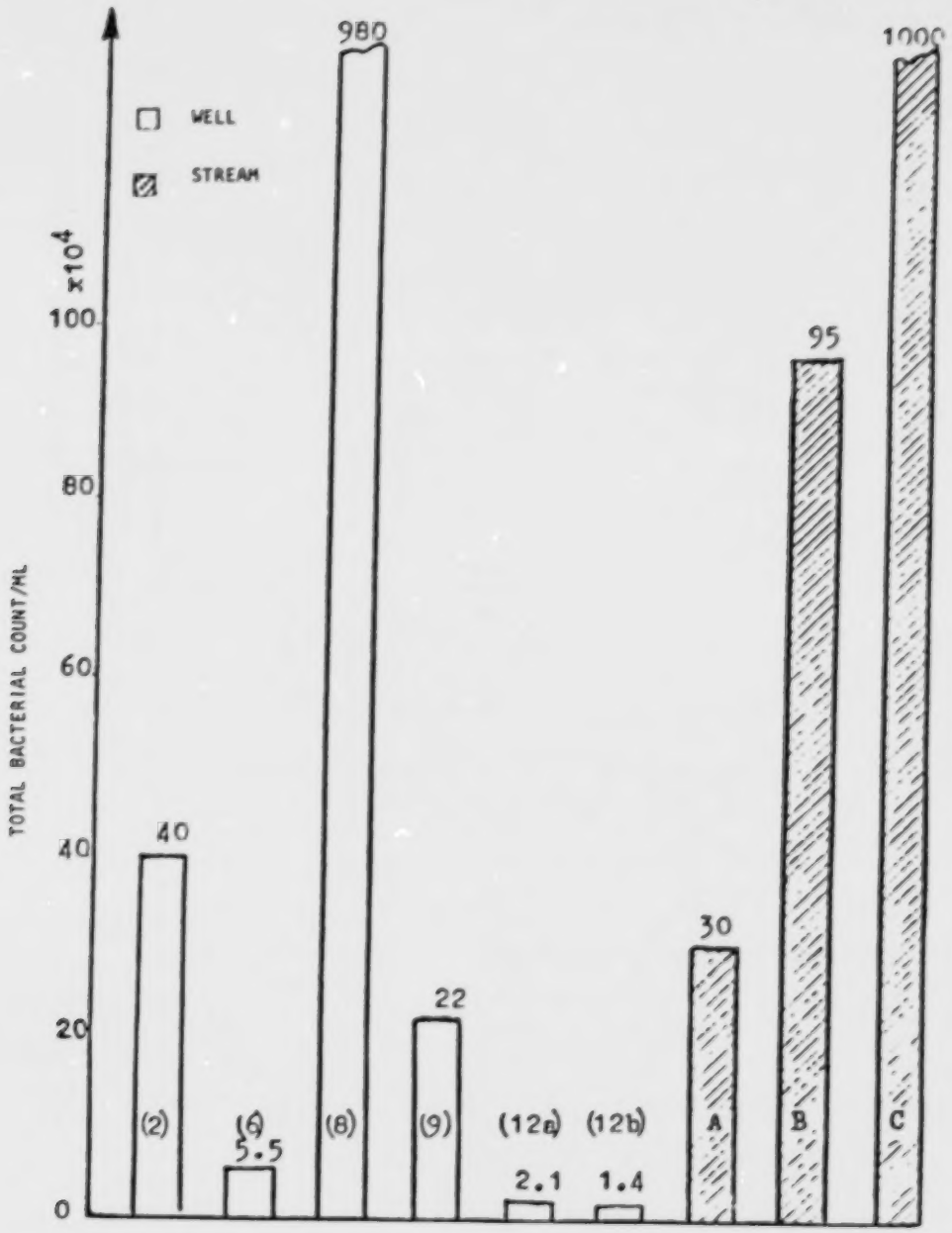

FIGURE 2. CONTAMINATION OF THE VILLAGE WATER SOURCES

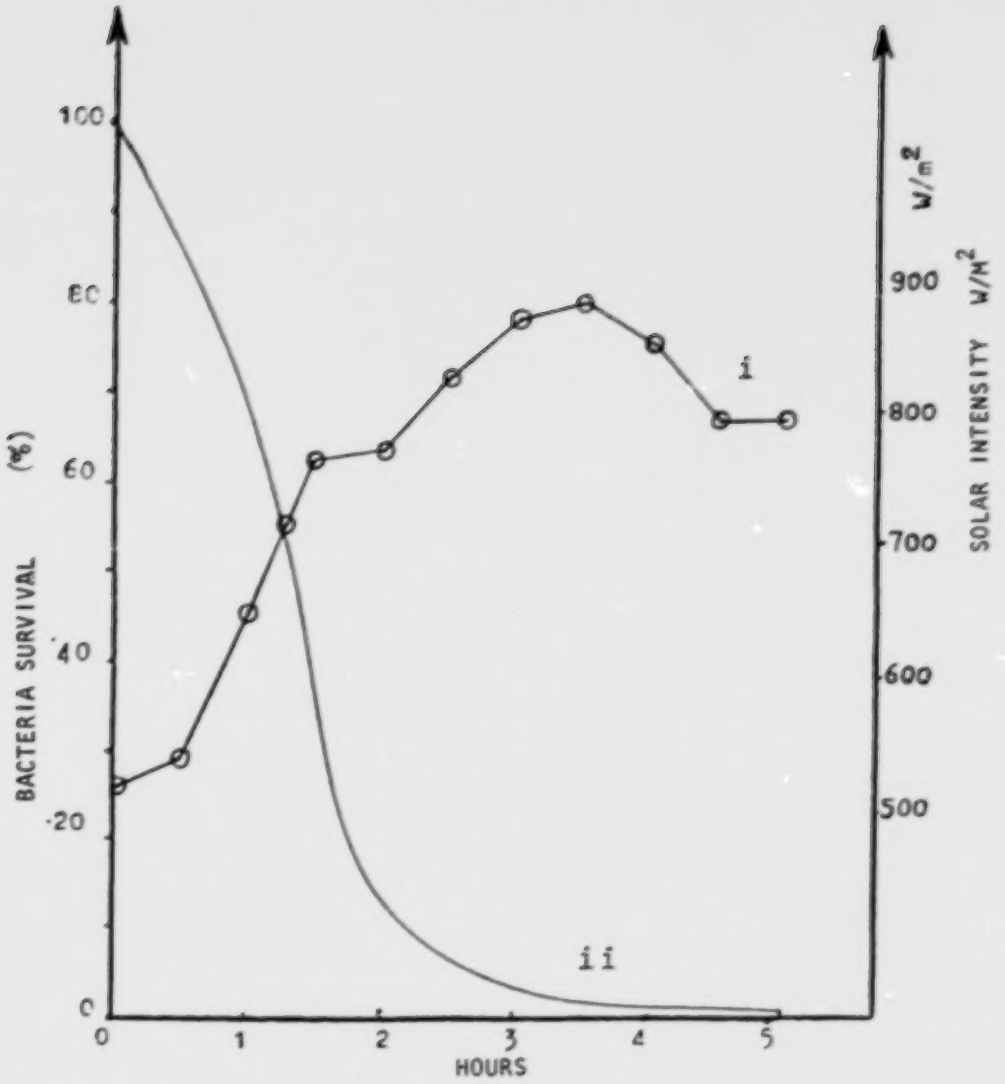

FIGURE 3. DESTRUCTION OF BACTERIA UPON EXPOSURE TO SUN

SOURCE NO. 8, CONTAINER: BLUISH PLASTIC

DATE: 14 JANUARY 1986

i. SOLAR INTENSITY

ii. BACTERIAL SURVIVAL

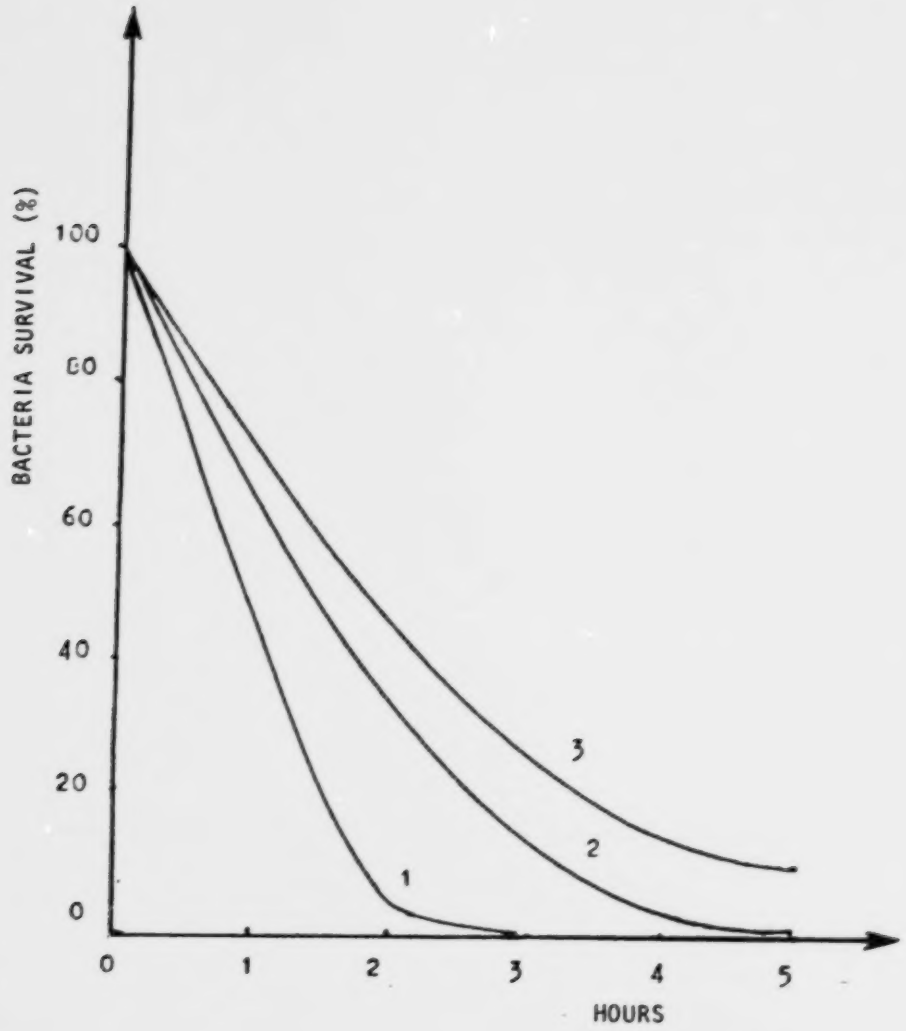

FIGURE 4. RATE OF DESTRUCTION OF E. COLI IN (1) SUN, (2) ROOM AND (3) DARK

SOURCE: WELL 8, CONTAINER: COLOURLESS GLASS BOTTLE

DATE: 8 MAY 1986

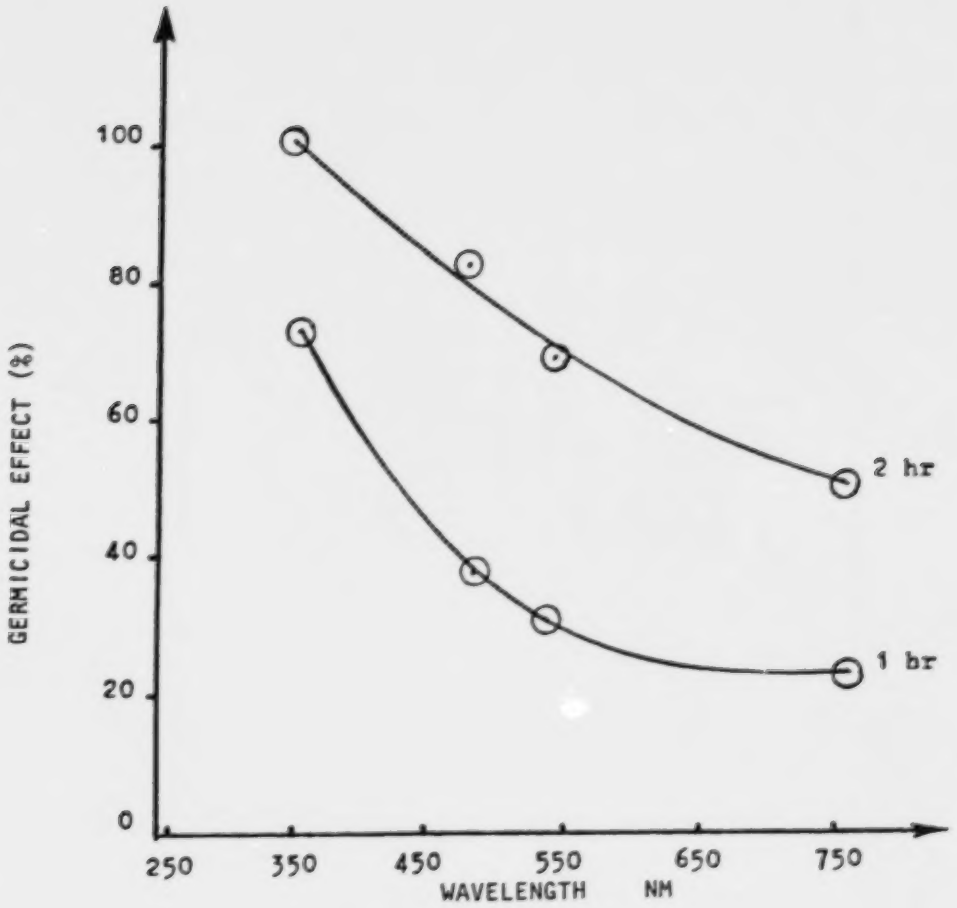

FIGURE 5. ACTION SPECTRUM SHOWING THE RELATIVE GERMICIDAL EFFECT OF TUNGSTEN LAMP ON TOTAL BACTERIAL COUNT AS A FUNCTION OF WAVELENGTH

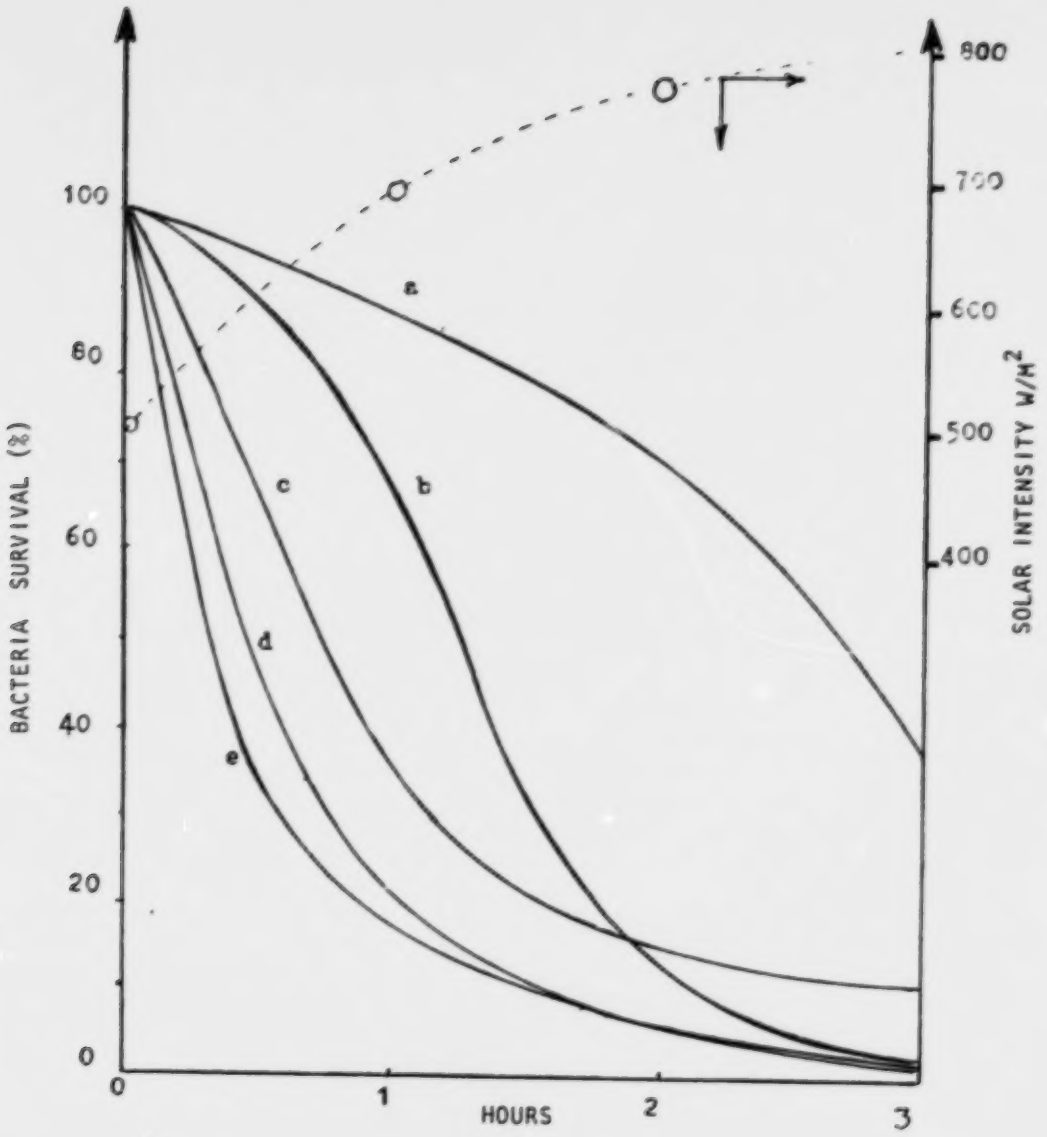

FIGURE 6. DESTRUCTION OF BACTERIA OF WATER EXPOSED TO SUN IN DIFFERENT CONTAINERS

(A) LIGHT BROWN GLASS (B) BLUISH PLASTIC

(C) DEEP GREEN GLASS (D) TURQUOISE GLASS

(E) COLOURLESS GLASS

----- SOLAR INTENSITY

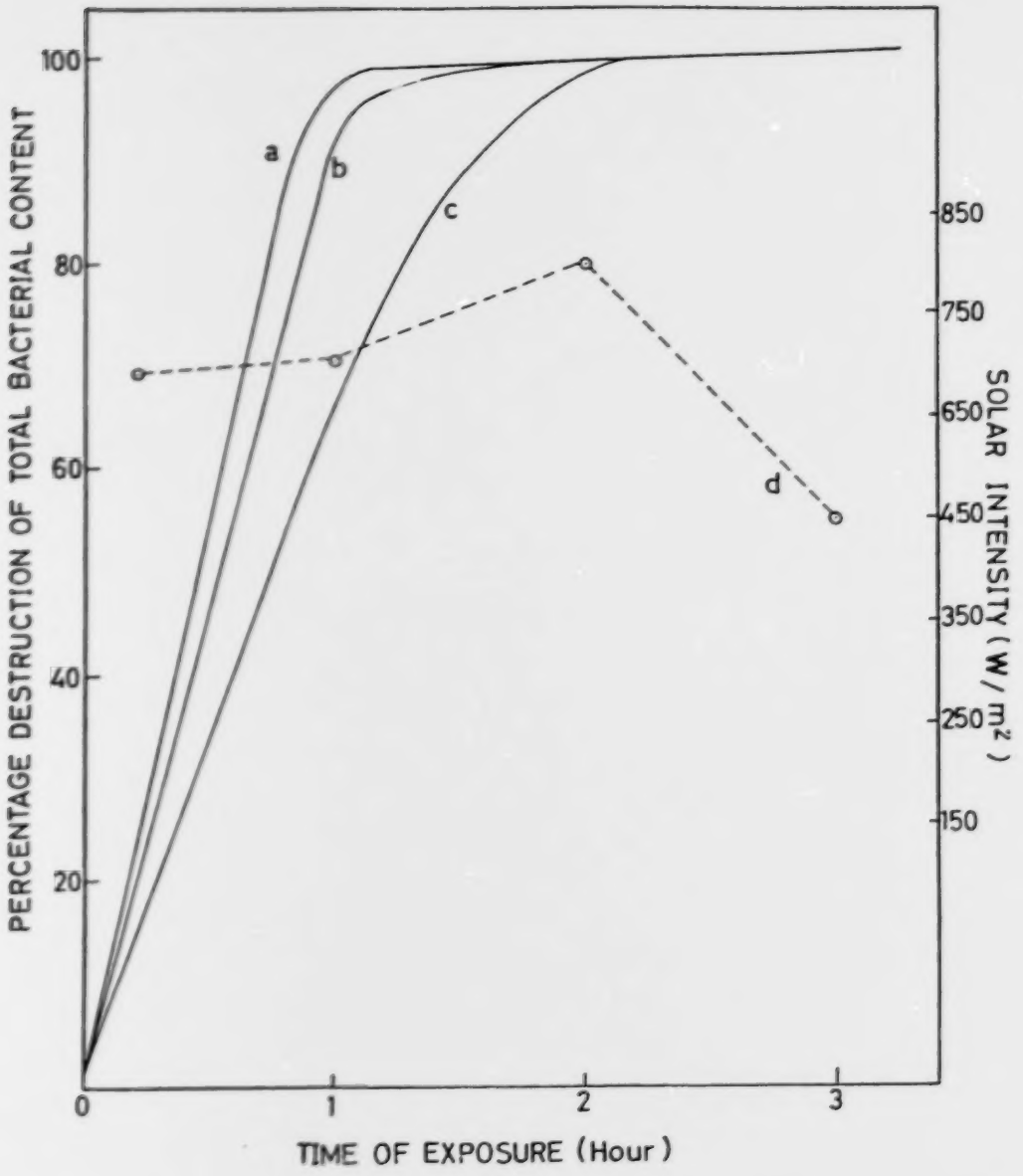

Fig. 7 Fate of TBC of artificially contaminated water with:
(a) Staphylococcus aureus
(b) Pseudongonas aeruiginaso
(c) Klebsiella preumoniae

The dashed curve shows the solar intensitiy in w/m² at time of exposure.

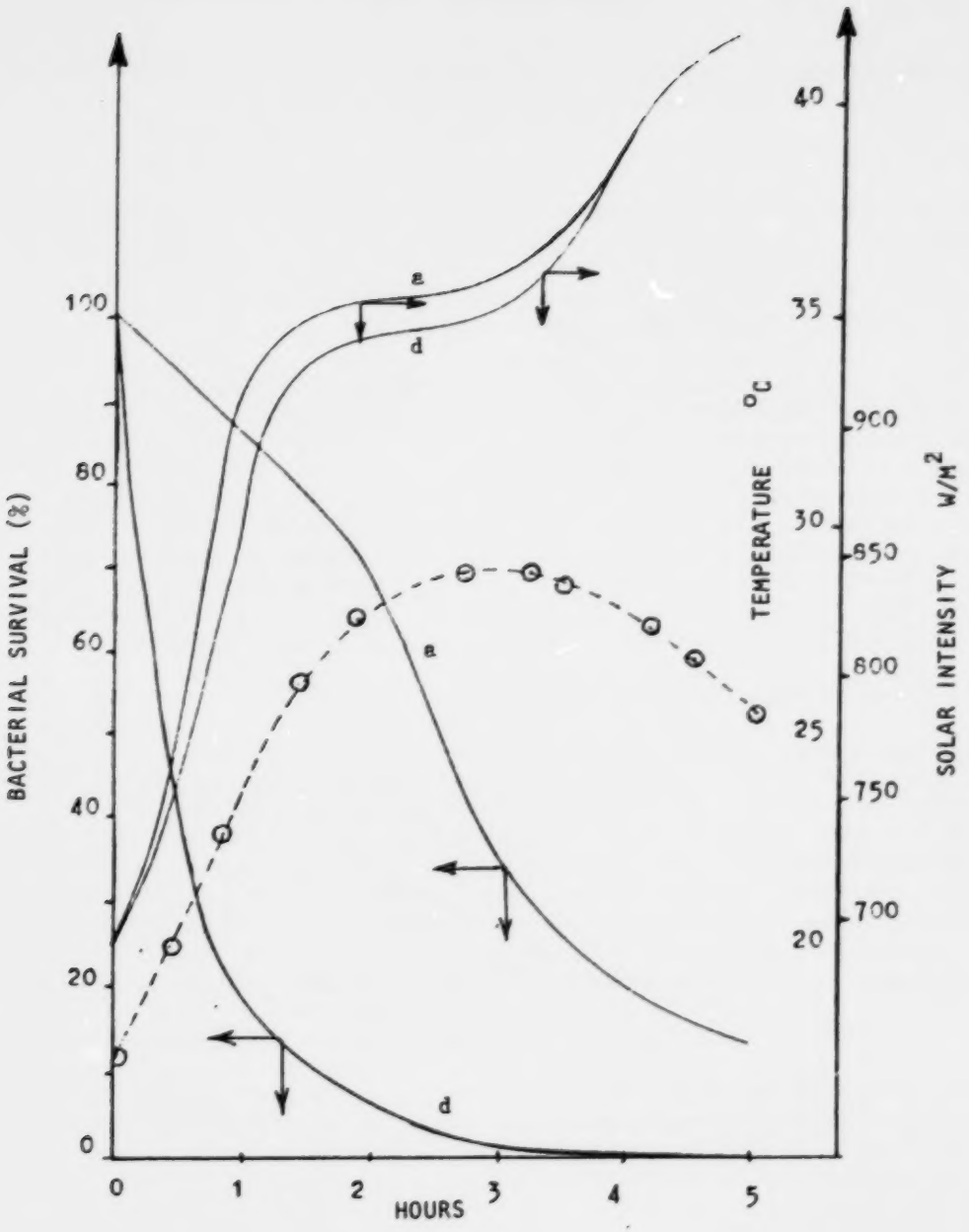

FIGURE 8. VARIATION OF TOTAL BACTERIAL COUNT AND TEMPERATURE FOR WATER IN CONTAINERS; (A) LIGHT BROWN GLASS, (D) TURQUOISE GLASS.

---- SOLAR INTENSITY

A PRELIMINARY ASSESSMENT OF THE BACTERIAL RESISTANCE TO SOLAR WATER PURIFICATION

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ABSTRACT

The effects of the following variables upon the bacterial inactivation by light-induced damages during the Solar Water Purification technique are preliminarily assessed: total and instantaneous solar radiation, water temperature, presence of suspended solids and solutes, and increased bacterial resistance. The results obtained, so far, seem to confirm that an incomplete Solar Water Purification process increases the bacterial resistance to solar inactivation. This may be an important factor to be considered for the introduction and field application of this alternative disinfection technique.

1. INTRODUCTION

1.1. The Solar Water Purification Technique

With the reports of the research team headed by Aftim Acra in Beirut, Lebanon (Acra et al. 1980, 1984 and 1987) attention was brought to the fact that solar radiation could be used as a source for water disinfection. Additional results (Baldi 1986, Cotis 1986, Odeyemi 1986a, 1986b and 1987, Arafa 1987, Koottatep 1988, Sepalage 1988, Zapp et al. 1988) confirmed Acra et al's findings and raised important questions related to the applicability of the technique. Some of these questions deal with: the type of pathogenic microorganisms that can be killed by solar radiation; exact amount of irradiation, in terms of exposure time and intensity, necessary to achieve a 100 % inactivation; social acceptance of the technique; effect of interference factors like turbidity, sedimentation, materials for the containers, biological defense and repair mechanisms, etc. A detailed bibliographic review on this and closely related subjects has been written (Hahn 1988).

Despite the basic and worldwide corroboration of the Solar Water Purification technique, well planned research is needed in order to answer above questions. Only then, it could be widely used as an alternative and reliable water disinfection technique for people without access to other potabilization methods.

1.2. Solar Disinfection

The biological effects of solar radiation, especially those related to the ultraviolet (UV) range (3-400 nm), have been thoroughly studied and are explained in detail elsewhere (Senger 1984, Jagger 1985). Most of the important biological molecules (mainly proteins and nucleic acids) absorb radiation in the near-UV range (300-400 nm) and, therefore, the most affected cellular processes seem to be respiration, membrane transport, duplication of

nucleic acids and protein synthesis (Jagger 1976, 1981 and 1983, Moss 1981, Peak 1987).

Because of this injuring effect of solar radiation, all biological organisms normally exposed to it have developed some kind of protective mechanism against light-induced damages. Examples are the synthesis of carotenoid pigments (Huber 1980) and the light-induced repair of nucleic acids (Moseley 1984, Harris 1987).

The application of UV radiation for disinfection purposes is known since the late 19th century (Sharp 1939) and has increasingly been used for air, water and food treatment. Therefore, the inactivation of pathogenic and indicator microorganisms with artificial UV has been quite well documented and is a common practice for secondary wastewater disinfection and treatment of water for non-drinking purposes (Chang et al. 1985, Harris 1987, Crandall 1986, Qualls et al. 1985, Scheible 1987). The use of solar UV radiation is not equally developed because the synergistic and antagonistic effects of different wavelengths are not completely understood, besides the fact that several uncontrolable factors (climatological, geographical, etc.) continuously influence its availability and hence its effectiveness.

1.3. Purpose and Objectives

The overall purpose of this report is to briefly present some of the results of a series of experiments carried out during summer 1988 at the Field Station of the Brace Research Institute (Ste. Anne de Bellevue, Québec, Canada), that aimed at assessing the possible effects of some of the above mentioned factors on the Solar Water Purification technique.

Specific objectives were:

1) to analyze pH and temperature changes during the process;
2) to assess the effect of solutes and suspended solids in water;
3) to study the effect of low solar radiation intensity on the bacterial inactivation;
4) to assess the bacterial capacity to recover from sub-lethal solar-induced damages;
5) to test a simple open flow-through recirculating system for Solar Water Purification.

2. PROCEDURES

To get comparable results, an experimental approach almost identical to that followed by other researchers was used (Acra et al. 1987, Cotis 1986, Baldi 1986, Odeyemi 1986a): distilled water, boiled tap-water and water from the St. Lawrence river (Ste. Anne de Bellevue) were contaminated with the effluent of a septic tank (1:100 dilution). For the batch experiments, one liter samples were exposed to solar radiation from 10:00 to 14:00 hours in vertically placed transparent glass containers (200 mm high, 80 mm wide, 80 mm deep and with a glass thickness of 3 mm) closed with a metallic cap, on a white-painted surface. For the flow-through system (Figure 1) two white plastic, hydroponic gullies (210 cm long, 5 cm wide and 3 cm high; 1:100 slope), were connected with a plastic tank in which a 10 liter water sample was placed and continuously recirculated by a submersible electric pump (flow rate of 2.5 liter/min).

Solar radiation on a horizontal surface was measured with a portable Haeni solarimeter and the water temperature was recorded with a mercury thermometer. 100 ml aliquots

were taken every hour for bacteriological analysis. A control sample was always kept in darkness, under laboratory conditions. The membrane filtration technique (APHA 1983) was used for estimating the total bacteria, total coliform and faecal coliform populations.

3. RESULTS

3.1. Temperature and pH

The maximum recorded temperatures in the water samples never exceeded 38.5°C for the batch system and 31.0°C for the flow-through system after 4 hours of exposure. Minimum recorded water temperature was 12.0°C. Typical daily temperature and radiation changes for a clear summer day are represented in Figure 2 and Table 1.

The pH of the water samples was found to be always between 6.0 and 6.5 and did not change with exposure time.

3.2. Suspended Solids and Solutes

Suspended solids from the septic tank effluent were eliminated by filtration through a Whatman No. 1 filter paper and the contamination and exposure procedure explained above was followed. The results are shown in Table 2 and Figures 3, 4 and 5. It was found that the tested bacteria (total bacteria, total coliforms and faecal coliforms) are inactivated quickly when the solids were filtered, even if the samples were not exposed to solar radiation. Bacteria in water with suspended solids tend to survive longer when exposed and their population did not decrease when they were not exposed.

The presence of solutes, given by the type of water used for the experiments, had some influence on the inactivation rate, but the results were not very clear (Figure 6, Table 3). Water from the St. Lawrence river (high level of solutes) was found to be too highly polluted with sewage effluents to be disinfected by this technique. Bacteria in tap water (intermediate level of solutes) seemed to be inactivated at a slower rate, especially during the last part of the exposure period, whereas bacteria in distilled water (low level of solutes) seemed to be more easily inactivated by solar radiation.

3.3. Low Radiation

The incident total solar radiation was found to be a critical parameter for the purification process (Figure 7, Table 4). For the specific conditions under which the tests, reported herein, were carried out, it was observed that an hourly total radiation average value of at least 0.5 kWh/m^2 was necessary for maintaining a noticeable reduction of the bacterial population.

When a low radiation period (cloudy conditions) occured during the Solar Water Purification process for more than one hour and the total bacteria and total coliforms were not completely inactivated during that interval, their regrowth was noticeable (Table 5 and Figures 8, 9 and 10). Again, an hourly total radiation of at least 0.5 kWh/m^2 and a minimum instantaneous radiation of 400 W/m^2 seemed to be necessary for maintaining the inactivation rate.

3.4. Increased Resistance

Total coliforms and faecal coliforms exposed to solar radiation for short periods of time (one and two hours) and allowed to recover during the following 24 hours, seemed to have increased their resistance to solar-induced inactivation (Figures 11 to 16 and Tables 6 and 7). More time and/or more solar radiation intensity were necessary for reducing their populations after the initial exposure.

This effect was more noticeable for total coliforms exposed to solar radiation of about 0.5 kWh/m^2 and 400 W/m^2 values mentioned above (Figures 13 and 14). Total coliforms exposed for 2.0 to 2.5 hours at lower solar radiation levels were more resistant than those exposed for one hour. Faecal coliforms did not show this last difference (Figures 15 and 16).

3.5. Open Flow-Through Recirculating System

With the flow-through system described earlier (Figure 1), no clear reduction in any of the tested bacterial populations was obtained.

4. DISCUSSION

In spite of the fact that entero-pathogenic bacteria seem to be much more sensitive to light-induced injuries than non-pathogenic and non-enteric bacteria, the following discussion is based mainly on the results obtained with total coliforms.

The total bacteria test was not very useful, especially because of the high density of colonies (high population) and the frequent growth of fungus on the plates that made it difficult to estimate their population.

The solar-induced inactivation of faecal coliforms was certainly quicker, but more resistant groups should always be used as indicators for assessing the reliability of this disinfection technique. This and the fact that the molecular biology of most bacteria is quite similar, are the reasons for discussing the results in general terms and not only in terms of faecal coliforms.

4.1. Temperature and pH

None of these two parameters was found to change significantly, therefore their importance for the Solar Water Purification process could not be assessed properly. The highest water temperatures occurred always at the end of the exposure period, when the inactivation was already completed, and they never exceeded by the normal body temperature by a large amount (optimal for most bacteria). Previous findings (Baldi 1986, Koottatep et al. 1988) and related reports (Pellon and Sinskey 1984, Ciochetti and Metcalf 1984) stress the fact that a significant increase in the water temperature (at least above 35°C during the first hour of exposure), could play an important role in the solar disinfection process by increasing the bacterial inactivation rate.

4.2. Suspended Solids and Solutes

The obtained results show that the presence of suspended solids could enhance bacterial

survival. The role of the sedimentation of these particles and the protective effect that the layer of sediments could offer to bacteria has to be researched carefully. Other reports (Acra et al. 1987, Cotis 1986, Odeyemi 1987, Baldi 1986, Zapp et al. 1988, etc.) have stressed the fact that turbid waters could not be completely disinfected by solar radiation alone. Whether the solids offer physical protection against radiation and/or nutrients to sub-lethally injured bacteria, and how this could be controlled, has to be clarified.

A similar question about dissolved nutrients and salts as protective factors against solar-induced damages and their role in the bacterial recovery process arises with the use of distilled, river and tap water. The fact that bacteria seem to die easier and recover slower when injured in distilled water has been discussed elsewhere (Odeyemi 1986a, 1986b and 1987) and could lead to erroneous information on the solar radiation intensities needed to disinfect different types of natural waters. Other reports have shown, however, that the presence of nutrients and salts does not interfere with the solar disinfection of rehydration solutions and buffers (Acra et al. 1980 and 1984, Chang et al. 1985).

4.3. Low Radiation

Previous publications (Odeyemi 1987, Zapp et al. 1988) reported lower radiation limits for the application of the Solar Water Purification technique. Some of these limits were rather difficult to define precisely (rainy conditions, clouds, humid and hot climate, etc.) but other statements (Odeyemi 1987) were clear: 600 W/m^2 should be the minimum amount of instantaneous radiation necessary for a reliable disinfection process.

Having in mind that many factors (type and material of the container, latitude, climate, season, etc.) influence this kind of result, it has to be stressed that the availability and intensity of the solar radiation are the key factors for this disinfection method. The results reported herein indicate that the instantaneous radiation as well as the total radiation are essential for defining some of the lower limits of the Solar Water Purification technique. In order to establish clearer limits both factors have to be researched thoroughly in connection with the bacterial repair and recovery systems.

4.4. Increased Resistance

At the same time as solar radiation induces damages in cellular membranes, nucleic acids and enzymatic systems, it also activates some of the repair systems, in a process known as "photoreactivation" (Jagger 1985, Moseley 1984, Senger 1984). Damages to the nucleic acids (especially to the Desoxyribo-Nucleic Acid, DNA) for example, occur mainly due to UV-radiation (254 nm). The respective repair mechanism is activated by light with wavelengths above 300 nm. The results of this damaging-repairing phenomenon are very complex synergistic and antagonistic relationships among different wavelengths of the incident solar radiation.

The research and discussion of the molecular photobiology of these processes is well beyond the scope of this paper, but the results reported herein confirm other reports (Baldi 1986) that stress the fact that previously exposed water contains bacteria that were not as easily inactivated as non-exposed bacteria. This might be a difficulty for the application of the Solar Water Purification technique. Whether the water source has been previously exposed to sun (rivers, channels, reservoirs) or not (wells, springs) will possibly determine the exposure time and/or the amount and intensity of solar radiation that will

be necessary to disinfect the water. This also indicates that the water treated through an incomplete Solar Water Purification process might be hazardous to the people that are using it for drinking purposes.

4.5. Open Flow-Through Recirculating System

The design and testing of flow-through systems that make use of solar radiation is discussed in detail elsewhere (Acra et al. 1987, Koottatep et al. 1988). Although the Solar Water Purification technique should be kept as simple as possible, the idea of a continuous operating system is indeed appealing.

The results obtained so far seem to show that even though a thin film of water was exposed continuously over a white surface during four hours, the fact that it was recirculated through a dark reservoir with a retention time (in the tank) of about 4 minutes did not allow any disinfection to occur. Whatever the reason might be for these results (continuous recontamination in the reservoir, lack of gully cover, small change in water temperature, increased bacterial resistance, brief exposure period, etc.), flow-through systems seem to be more prone to an unreliable performance than batch systems and will require much more research.

5. CONCLUSIONS

Having in mind the specific conditions under which this research was carried out and other natural restrictions (the inherent difficulty for statistical analysis due to uncontrollable climatological parameters and the impossibility of exact experimental replication), the following conclusions were made:

a) Changes in the water temperature and pH of the samples during the Solar Water Purification process were negligible and therefore appear not to affect the bacterial inactivation.

b) The presence of suspended solids and solutes in the water samples seemed to enhance the survival of the bacteria.

c) An hourly total radiation value of at least 0.5 kWh/m^2 and an instantaneous radiation of at least 400 W/m^2, appeared to be necessary for achieving a bacterial inactivation.

d) Bacteria injured by sunlight seemed to be able to repair the damages and recover their growth rate in about one hour, when the incident radiation decreased below the limits mentioned in c).

e) Bacteria exposed and allowed to recover appeared to be more resistant to light-induced inactivation and needed more exposure time and solar radiation intensity to be completely inactivated again.

f) The preliminary tests of the open flow-through recirculating system appeared to show that such a system could keep a continuously recovering and polluting bacterial population.

g) It was noted that faecal coliforms and total coliforms changed their colony appearance with the exposure to solar radiation. The possible significance of this fact is discussed elsewhere (Rychert and Stephenson 1981) and has to be further researched in connection to the Solar Water Purification technique. But it seems that total coliforms, more than faecal coliforms, should be used as indicator bacteria for assessing the reliability of this disinfection method.

ACKNOWLEDGEMENTS

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TABLE 1 TEMPERATURE AND SOLAR RADIATION VARIATIONS.[1]

Time of day	Temperature (°C)			Solar radiation	
	Control	Experimental	Ambient	Instant/s (W/m^2)	Total (kWh/m^2)
10:00	22.5	22.5	30.0	680	0.00
11:00	23.5	32.0	32.0	793	0.61
12:00	-	36.0	32.0	380	1.47
13:00	26.5	34.0	30.0	244	1.75
15:00	27.5	37.5	37.0	870	2.61

[1]Data from measurements taken on 14 June 1988

TABLE 2 EFFECT OF SUSPENDED SOLIDS ON THE SURVIVAL OF TOTAL BACTERIA (TB), TOTAL COLIFORMS (TC) AND FAECAL COLIFORMS.[1]

Time of day	Bacterial survival (%)											
	F/NE			NF/NE			F/E			NF/E[2]		
	TB	TC	FC	TB	TC	FC	TB	TC	FC	TB	TC	FC
10:00	100	100	100	100	100	100	100	100	100	100	100	100
11:00	38	1	0	100	100	100	28	2	0	70	16	5
12:00				100	100	56				44	1	0
12:30	7	0	0				7	0	0			
13:00				100	100	36				39	2	0
14:00	2	0	0				4	0	0			
15:00				100	98	20				21	0	0

[1]Data from measurements taken on 24 May 1988

[2]Filtered/non-exposed (F/NE), non-filtered/non-exposed (NF/NE), filtered/exposed (F/E), non-filtered/exposed (NF/E)

TABLE 3 EFFECT OF SOLUTES ON THE SURVIVAL OF TOTAL COLIFORMS.[1]

Time of day	Bacterial survival (%)		
	Distilled water	Tap water	River water
10:00	100	100	100
11:00	13	12	100
12:00	1	7	100
13:00	1	4	100
14:00			
15:00			100

[1]Data from measurements taken on July 20, 1988

TABLE 4 EFFECT OF TOTAL SOLAR RADIATION ON THE SURVIVAL OF TOTAL COLIFORMS.[1]

Time of day	Bacterial survival (%)	Total radiation (kWh/m^2)	Bacterial survival (%)	Total radiation (kWh/m^2)
10:00	100	0	100	0
11:00	5	0.70	9	0.45
12:00			7	1.25
12:30	0	1.80		
13:00			0	1.70

[1]Data from measurement taken on July 4 and 20, 1988

TABLE 5 EFFECT OF A PERIOD OF LOW SOLAR RADIATION INTENSITY ON THE SURVIVAL OF TOTAL BACTERIA (TB), TOTAL COLIFORMS (TC) AND FAECAL COLIFORMS (FC).[1]

Time of day	Instantaneous radiation (W/m^2)	Total radiation (kWh/m^2)	Bacterial survival (%)		
			TB	TC	FC
10:00	680	0	100	100	100
11:00	793	0.61	71	13	5
12:00	380	1.47	35	1	0
13:00	244	1.75	45	2	0
15:00	870	2.61	20	0	0

[1]Data from measurements taken on June 14, 1988

TABLE 6 SURVIVAL OF TOTAL COLIFORMS (TC) AND FAECAL COLIFORMS (FC) AFTER PREVIOUS EXPOSURE TO SHORT PERIODS OF SOLAR RADIATION.[1]

Time of day	Total radiation (kWh/m^2)	Bacterial survival (%)			
		TC		FC	
10:00	0	100		100	
11:00	0.62	5		2	
12:30	1.80	0		0	
		a	b	a	b^2
10:00	0	100	100	100	100
11:00	0.72	-	-	100	100
12:00	1.52	15	23	0	0
13:00	2.75	3	1	0	0
14:00	3.52	0	2	0	0

[1]Data from measurements taken on July 4 and 5, 1988

[2]a = 1 hour of exposure on the previous day; b = 2.5 hours of exposure on the previous day

TABLE 7. SURVIVAL OF TOTAL COLIFORMS AFTER A PREVIOUS EXPOSURE TO SHORT PERIODS OF LOW INTENSITY SOLAR RADIATION.[1]

Time of day	Total radiation (kWh/m^2)	Survival of total coliforms (%)	
10:00	0	100	
11:00	0.27	100	
12:30	0.55	100	
		a	b[2]
10:00	0	100	100
11:00	0.62	39	100
12:00	1.50	0	90
13:00	2.60	0	0
14:00	3.25	0	0

[1]Data from measurements taken on July 21 and 22, 1988

[2]a = 1 hour of exposure on the previous day; b = 2 hours of exposure on the previous day

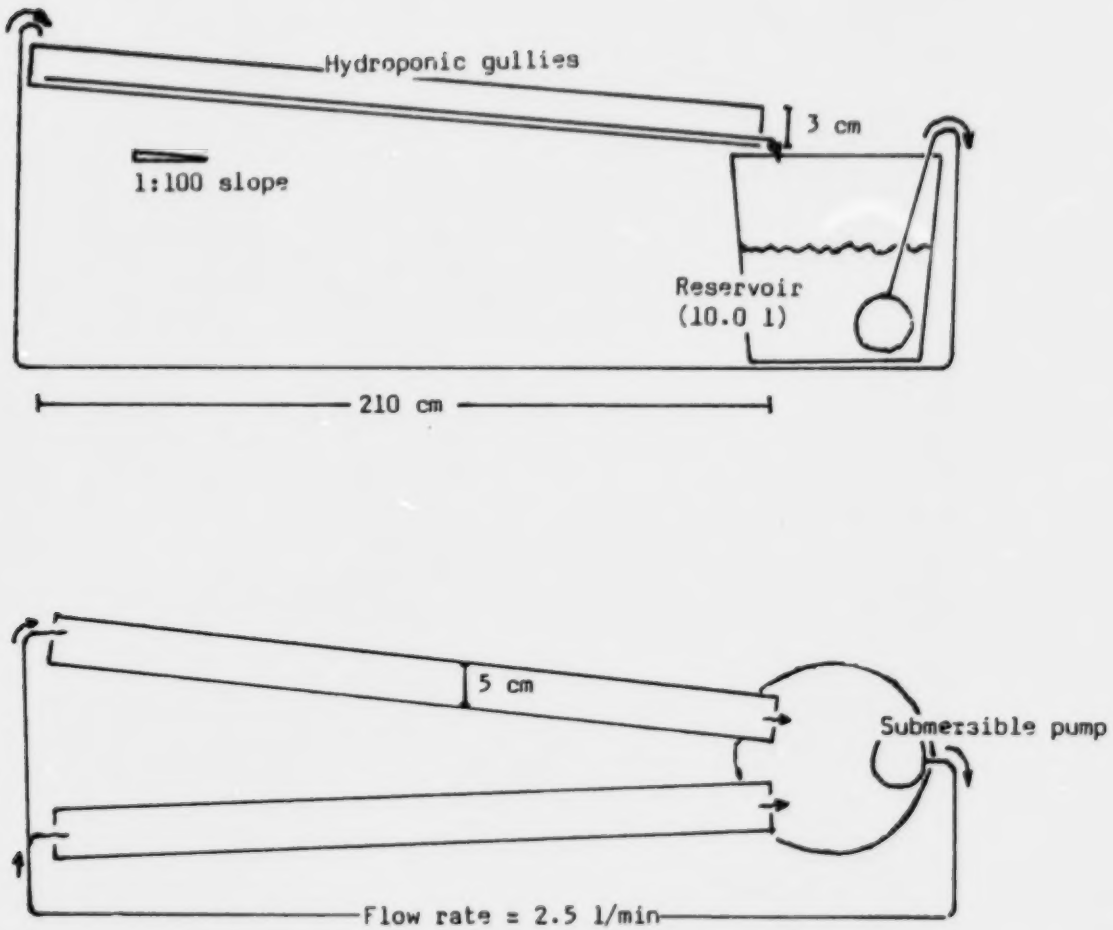

Figure 1. Sketch of an open flow-through recirculating system.

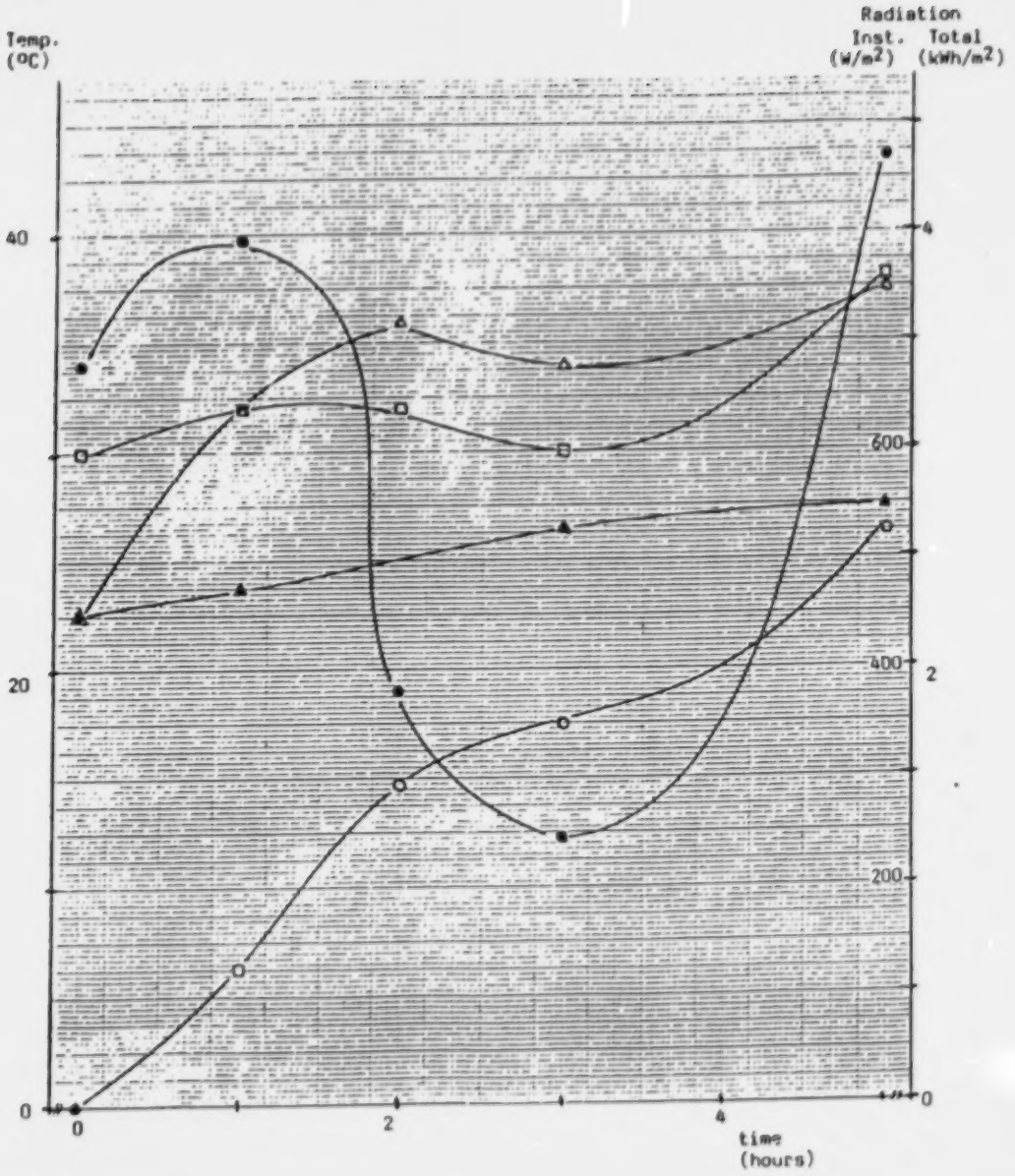

Figure 2. Example of daily variations in temperature and radiation measurements.
(-▲-) Control temperature. (-□-) Ambient temperature.
(-Δ-) Experimental temperature.
(-o-) Total radiation. (-●-) Instantaneous radiation.
Data from Table 1.

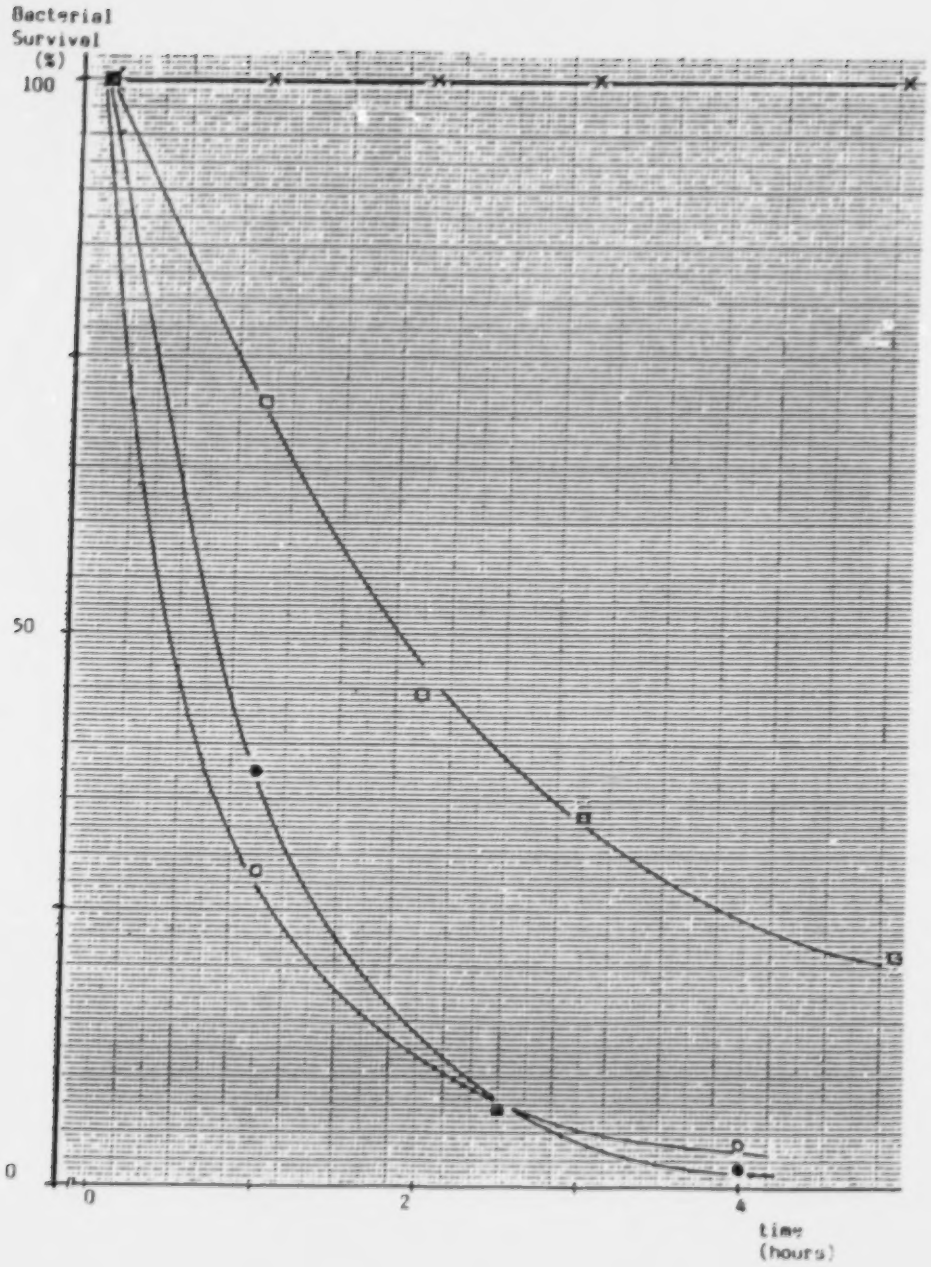

Figure 3. Effect of suspended solids on the survival of total bacteria.
(—●—) Filtered/Non-exposed. (—x—) Non-filtered/Non-exposed.
(—o—) Filtered/Exposed. (—□—) Non-Filtered/Exposed.
Data from Table 2.

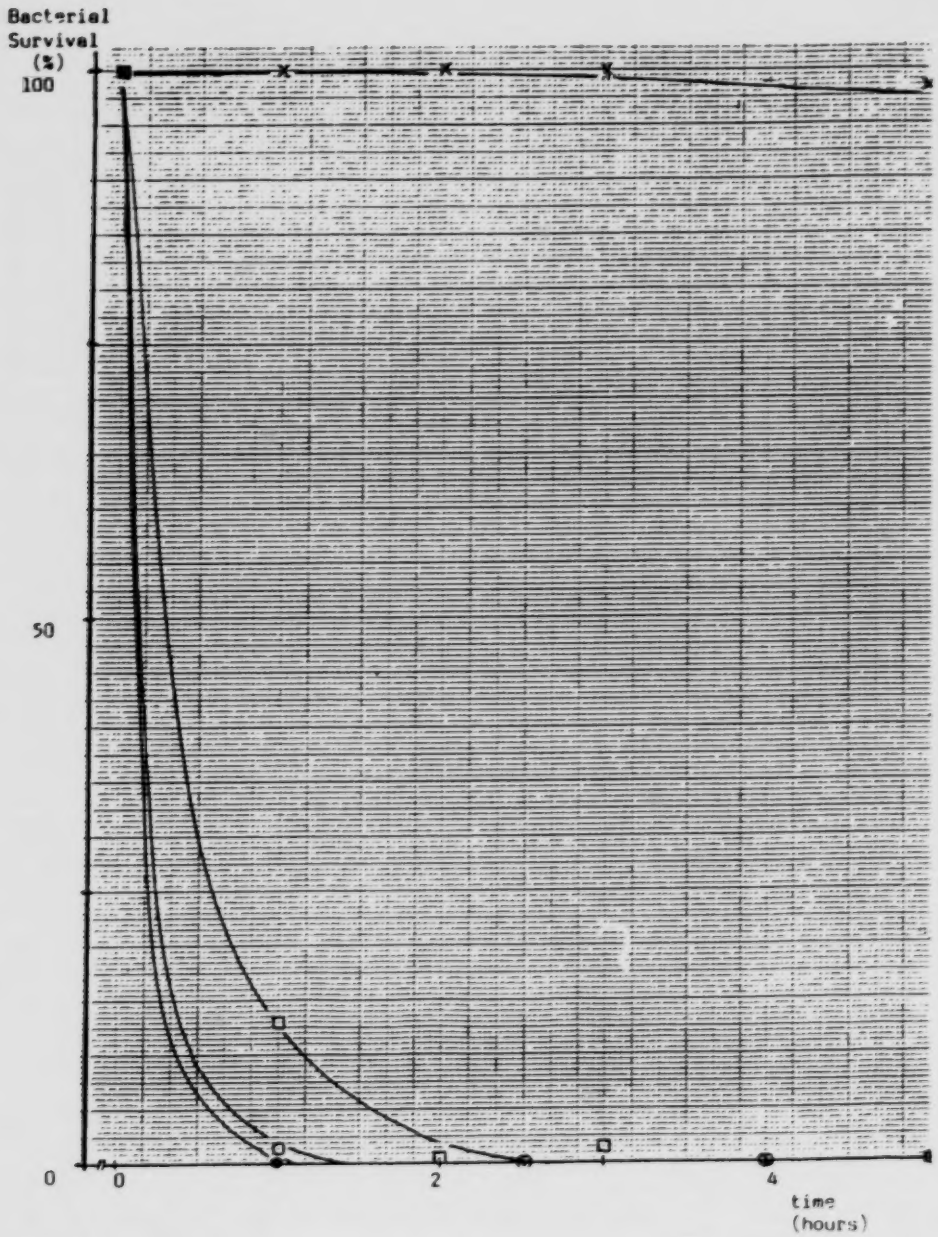

Figure 4. Effect of suspended solids on the survival of total coliforms.
(—●—) Filtered/Non-exposed. (—✖—) Non-filtered/Non-exposed.
(—o—) Filtered/Exposed. (—□—) Non-Filtered/Exposed.
Data from Table 2.

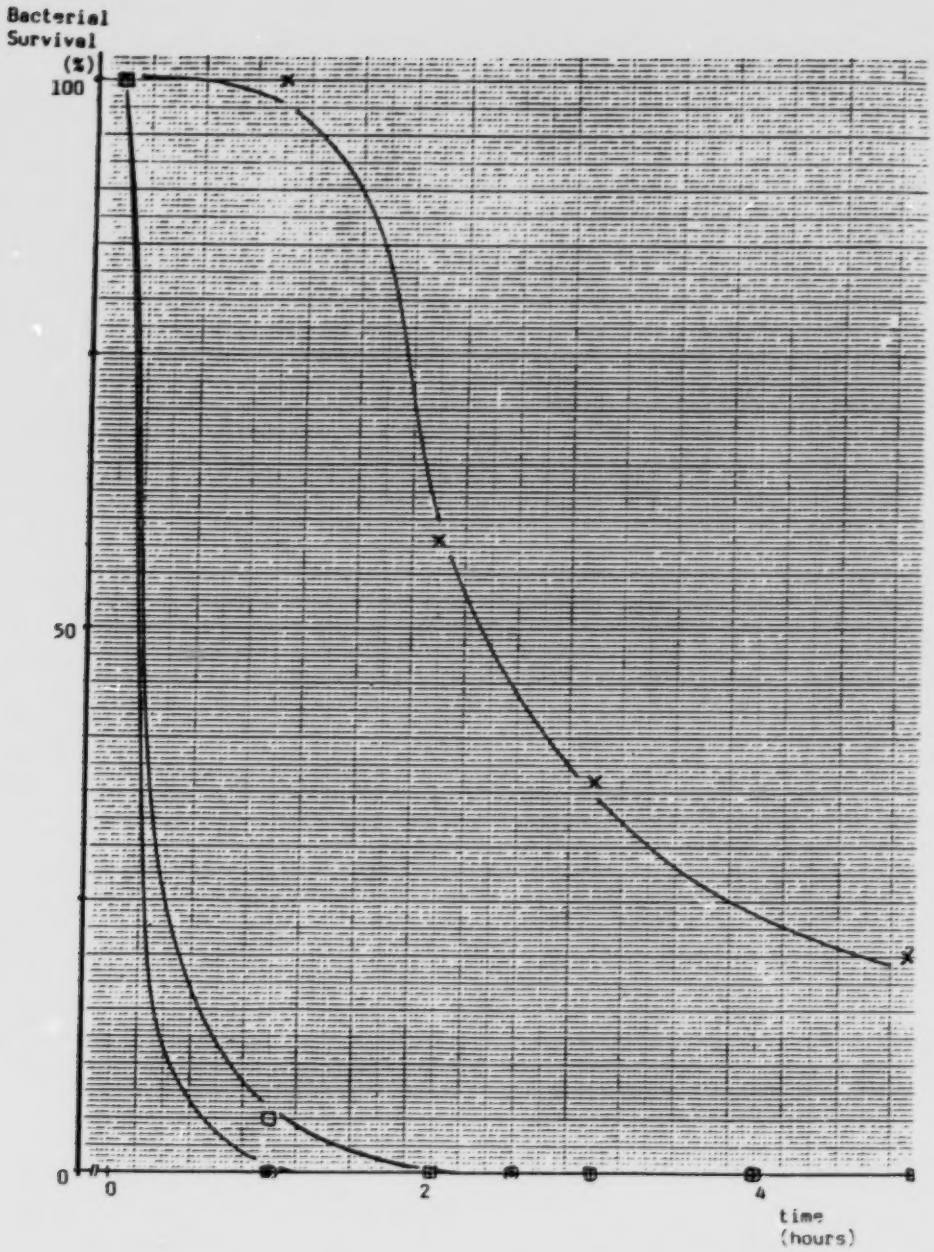

Figure 5. Effect of suspended solids on the survival of faecal coliforms.
(—●—) Filtered/Non-exposed. (—x—) Non-filtered/Non-exposed.
(—○—) Filtered/Exposed. (—□—) Non-Filtered/Exposed.
Data from Table 2.

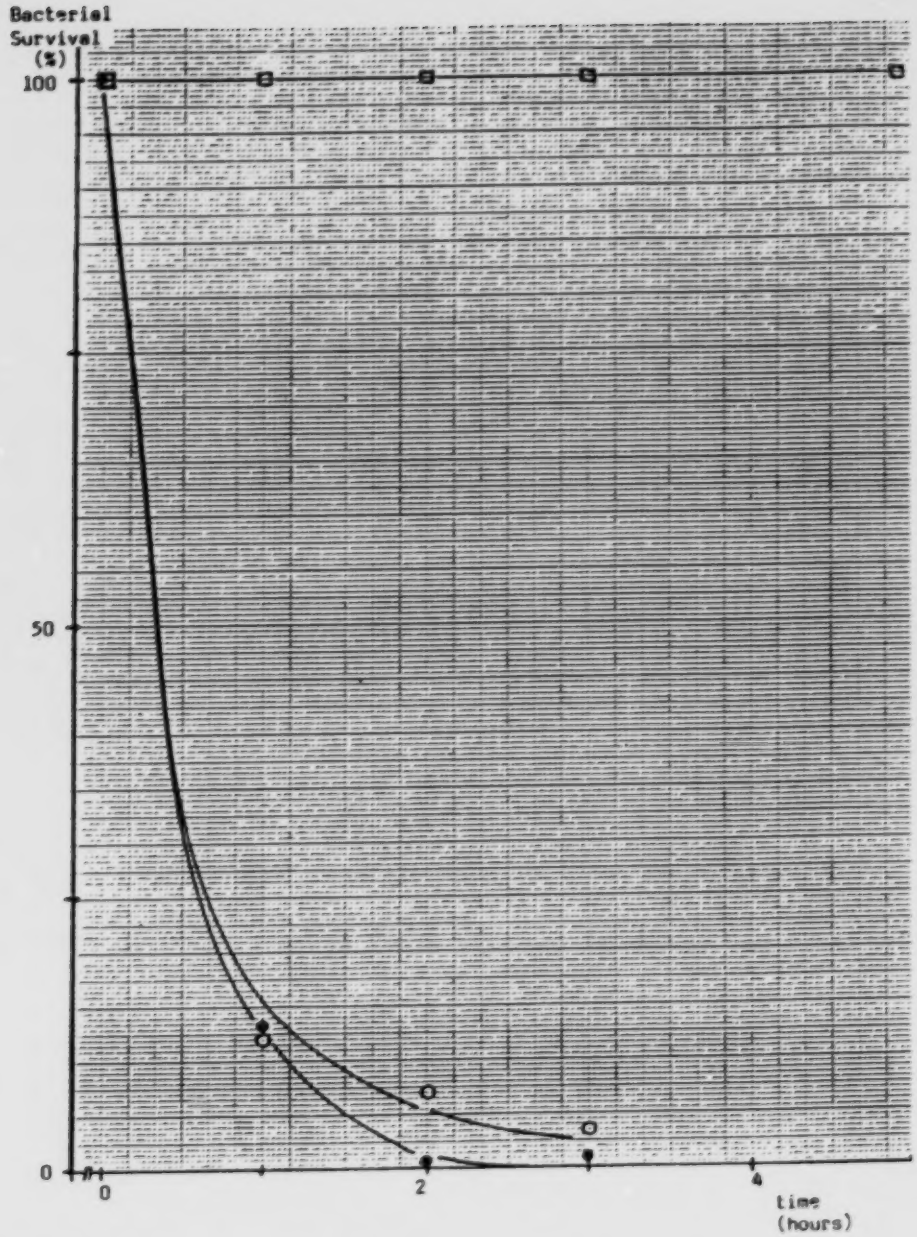

Figure 6. Effect of solutes on the survival of total coliforms. (—●—) Distilled water. (—○—) Tap water. (—□—) River water. Data from Table 3.

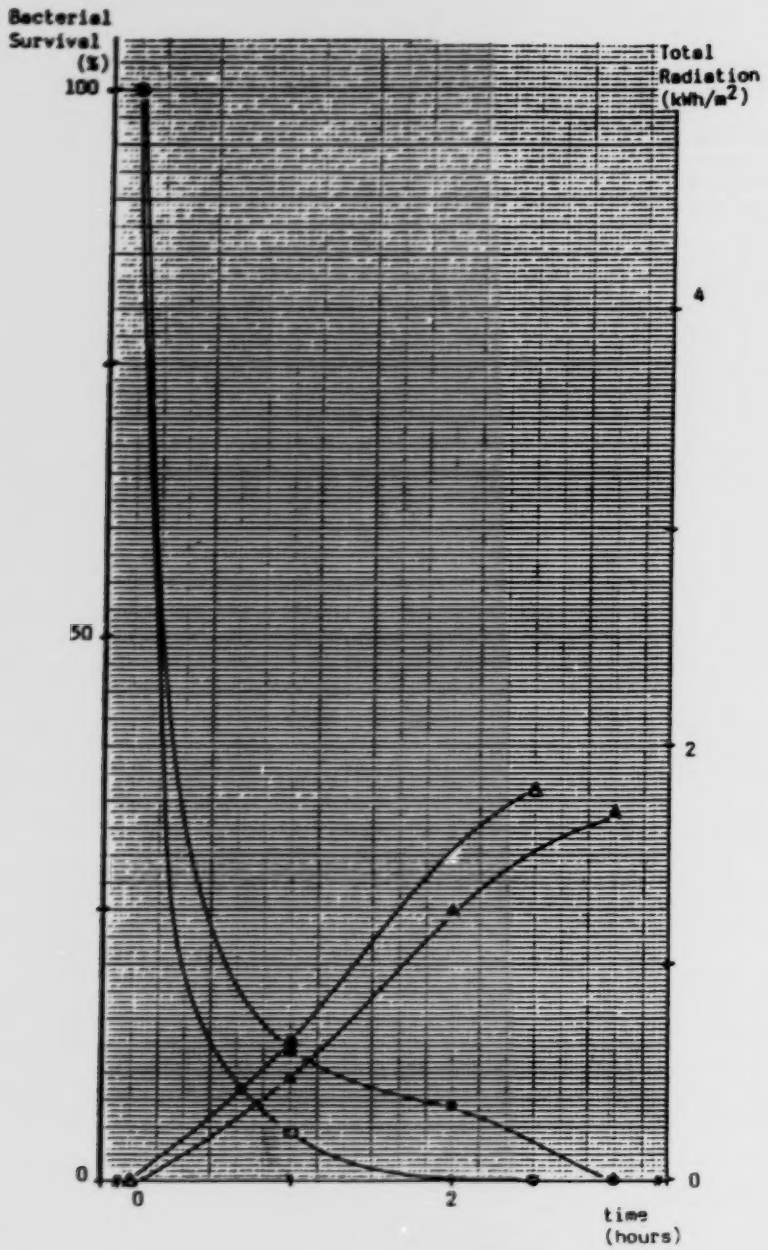

Figure 7. Effect of total solar radiation on the survival of total coliforms.
(—●—) Bacterial survival. (—▲—) Total radiation.
Data from Table 4.

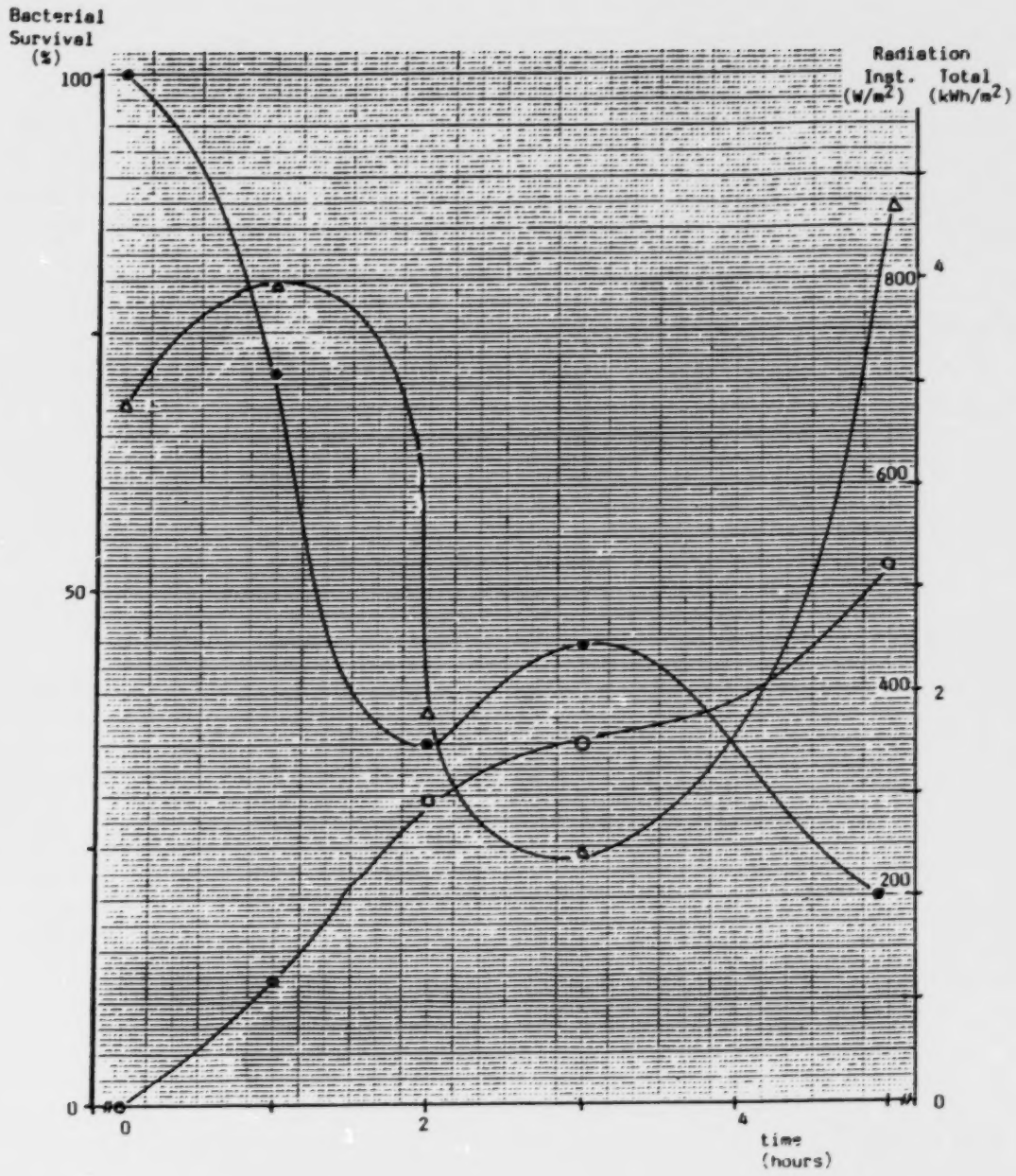

Figure 8. Effect of a period of low solar radiation intensity on the survival of total bacteria.
(—●—) Bacterial survival. (—o—) Total radiation.
(—Δ—) Instantaneous radiation.
Data from Table 5.

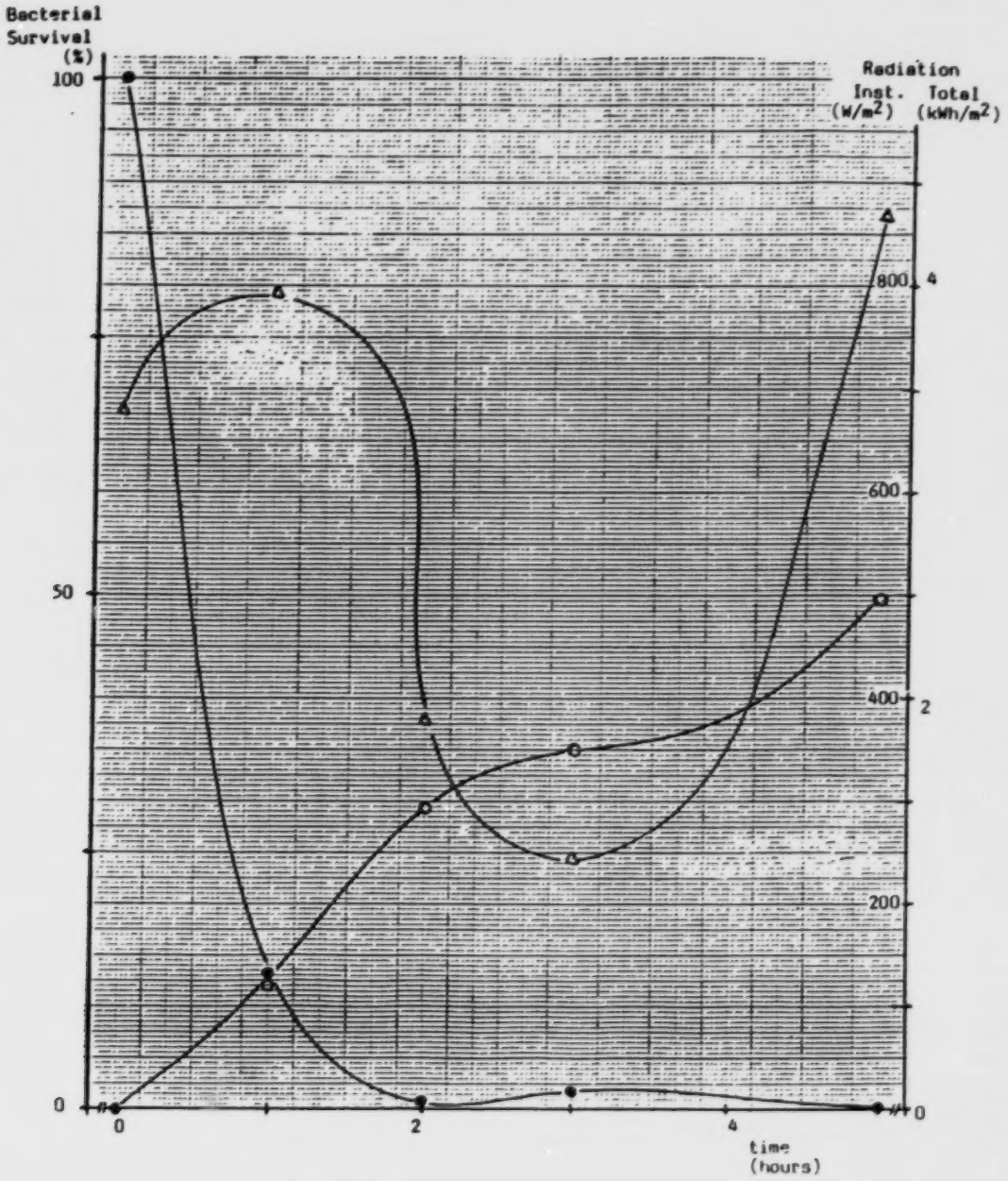

Figure 9. Effect of a period of low solar radiation intensity on the survival of total coliforms.
(—●—) Bacterial survival. (—o—) Total radiation.
(—Δ—) Instantaneous radiation.
Data from Table 5.

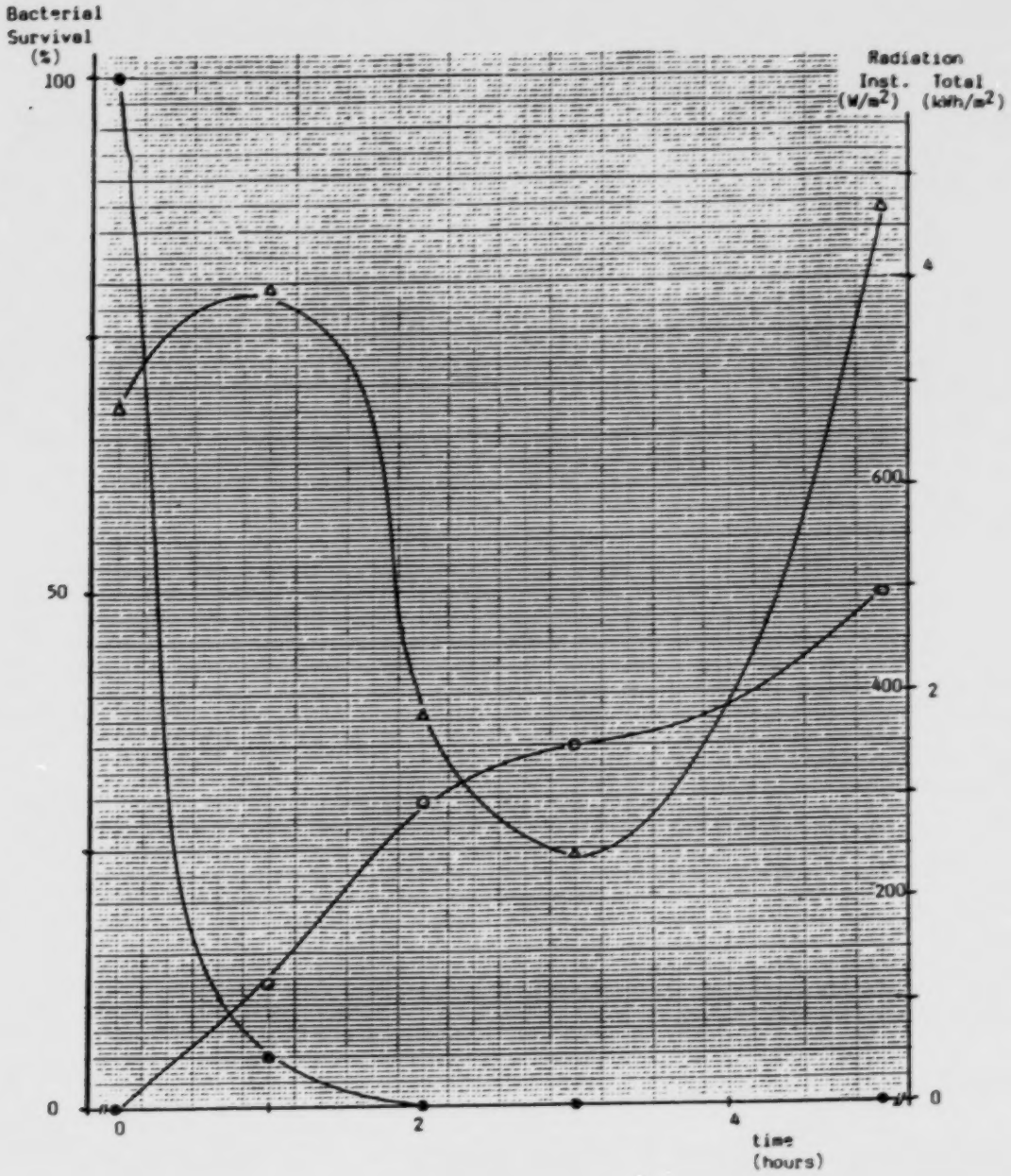

Figure 10. Effect of a period of low solar radiation intensity on the survival of faecal coliforms.
(—●—) Bacterial survival. (—o—) Total radiation.
(—Δ—) Instantaneous radiation.
Data from Table 5.

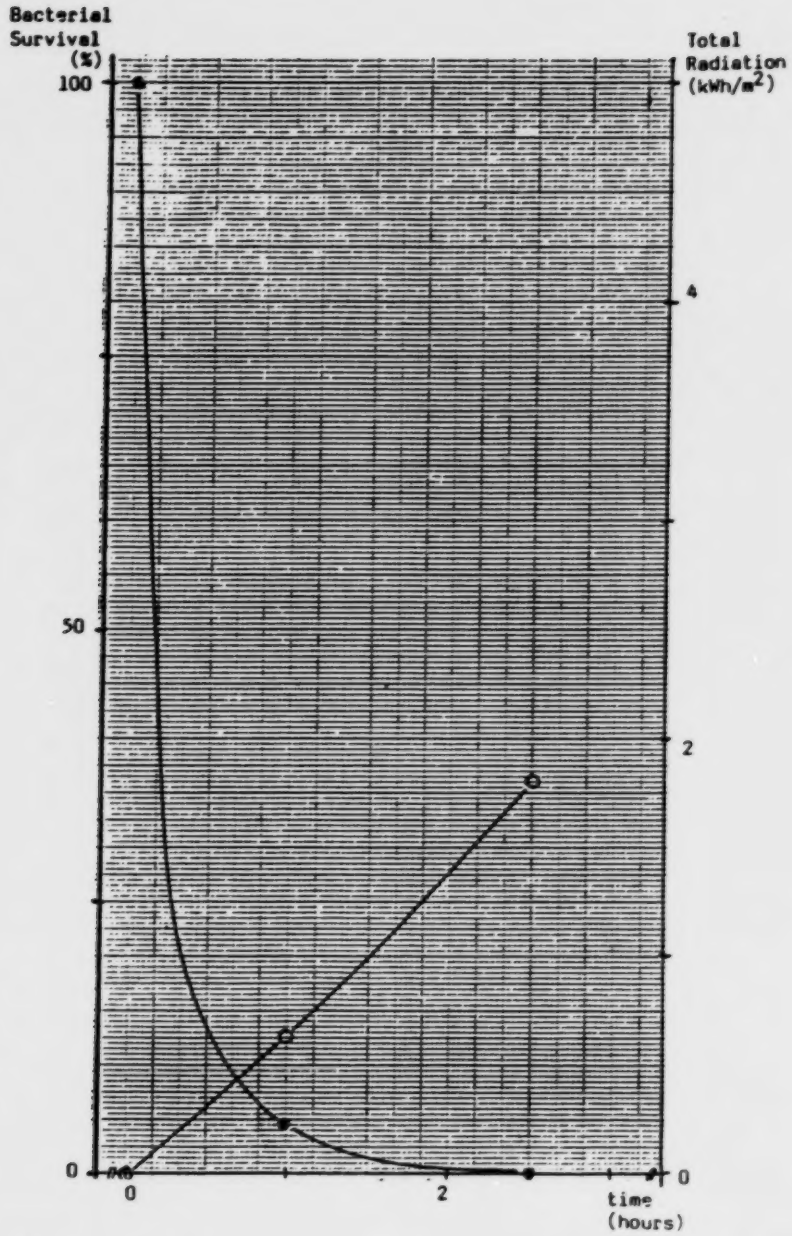

Figure 11. Initial inactivation of total coliforms exposed to brief periods of solar radiation.
(—●—) Bacterial survival. (—○—) Total radiation.
Data from Table 6.

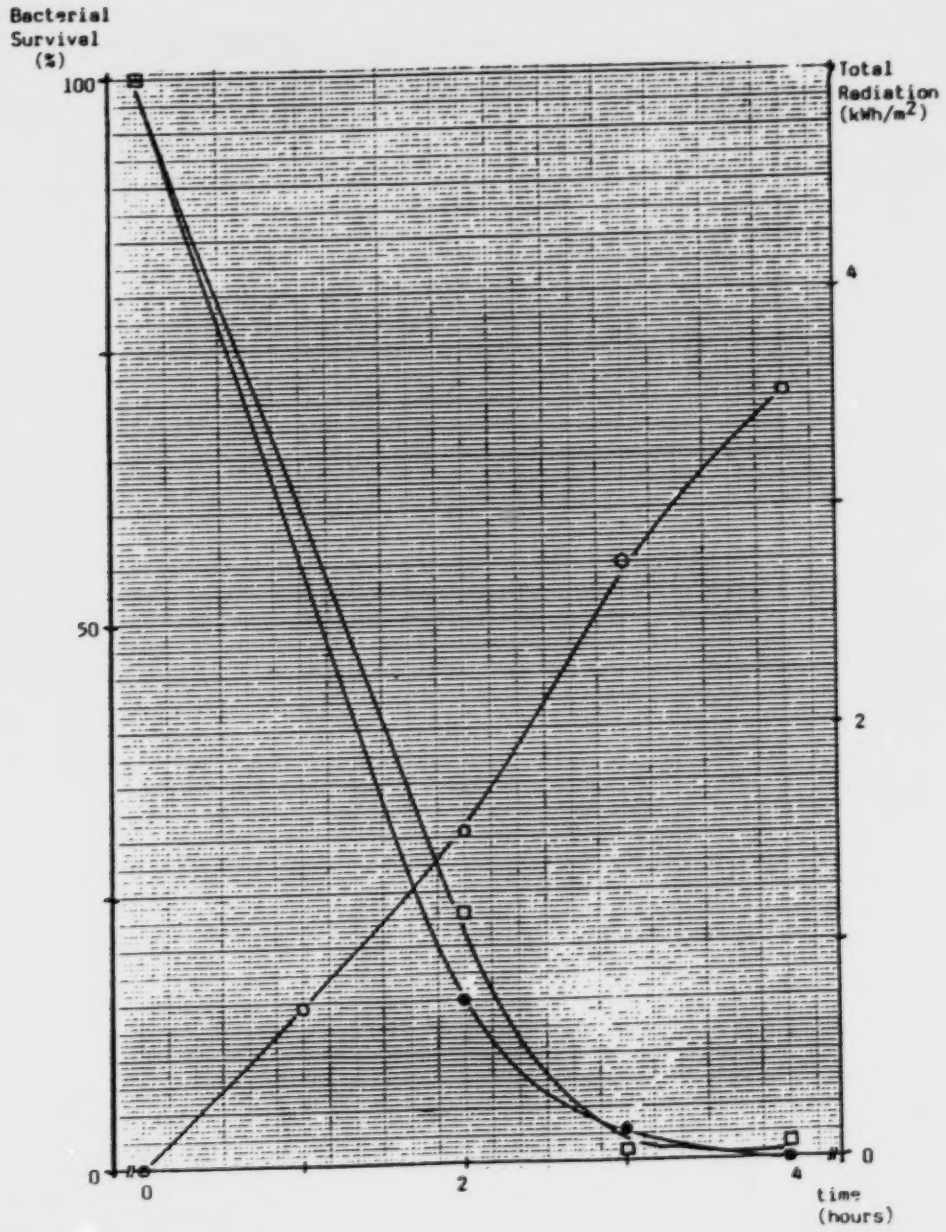

Figure 12. Final inactivation of total coliforms previously exposed to brief periods of solar radiation.
(—●—) Bacterial survival after one hour of previous exposure.
(—□—) Bacterial survival after 2.5 hours of previous exposure.
(—○—) Total radiation.
Data from Table 6.

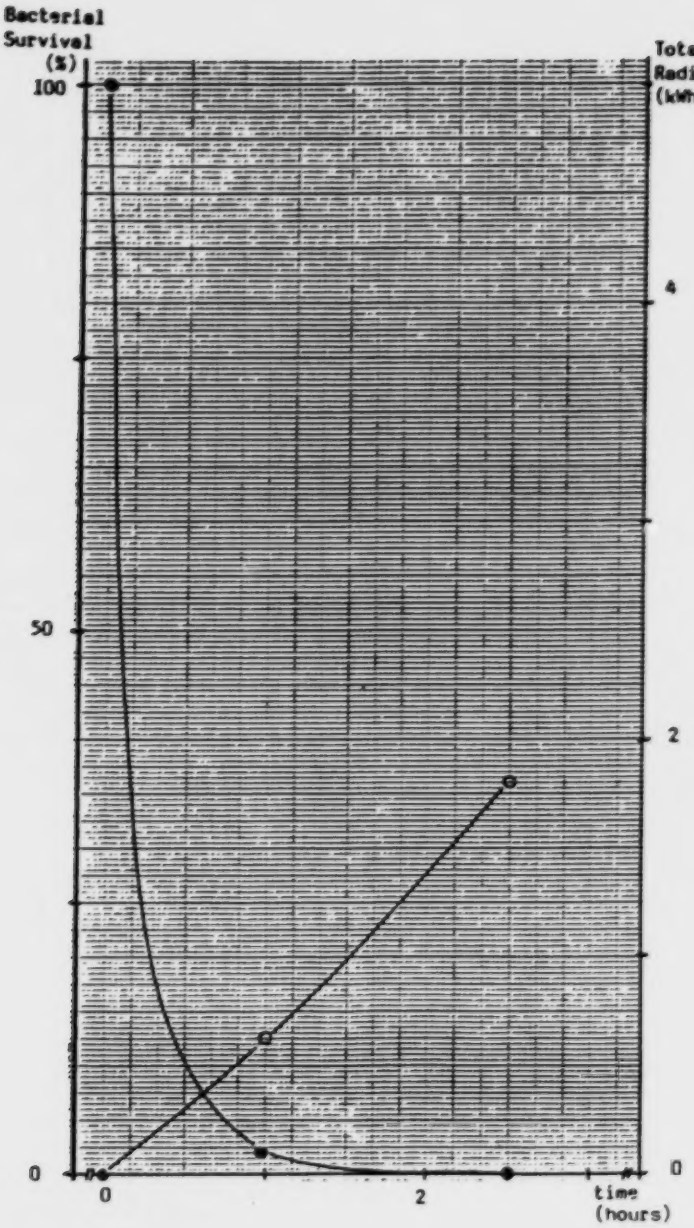

Figure 13. Initial inactivation of faecal coliforms exposed to brief periods of solar radiation.
(—●—) Bacterial survival. (—o—) Total radiation.
Data from Table 6.

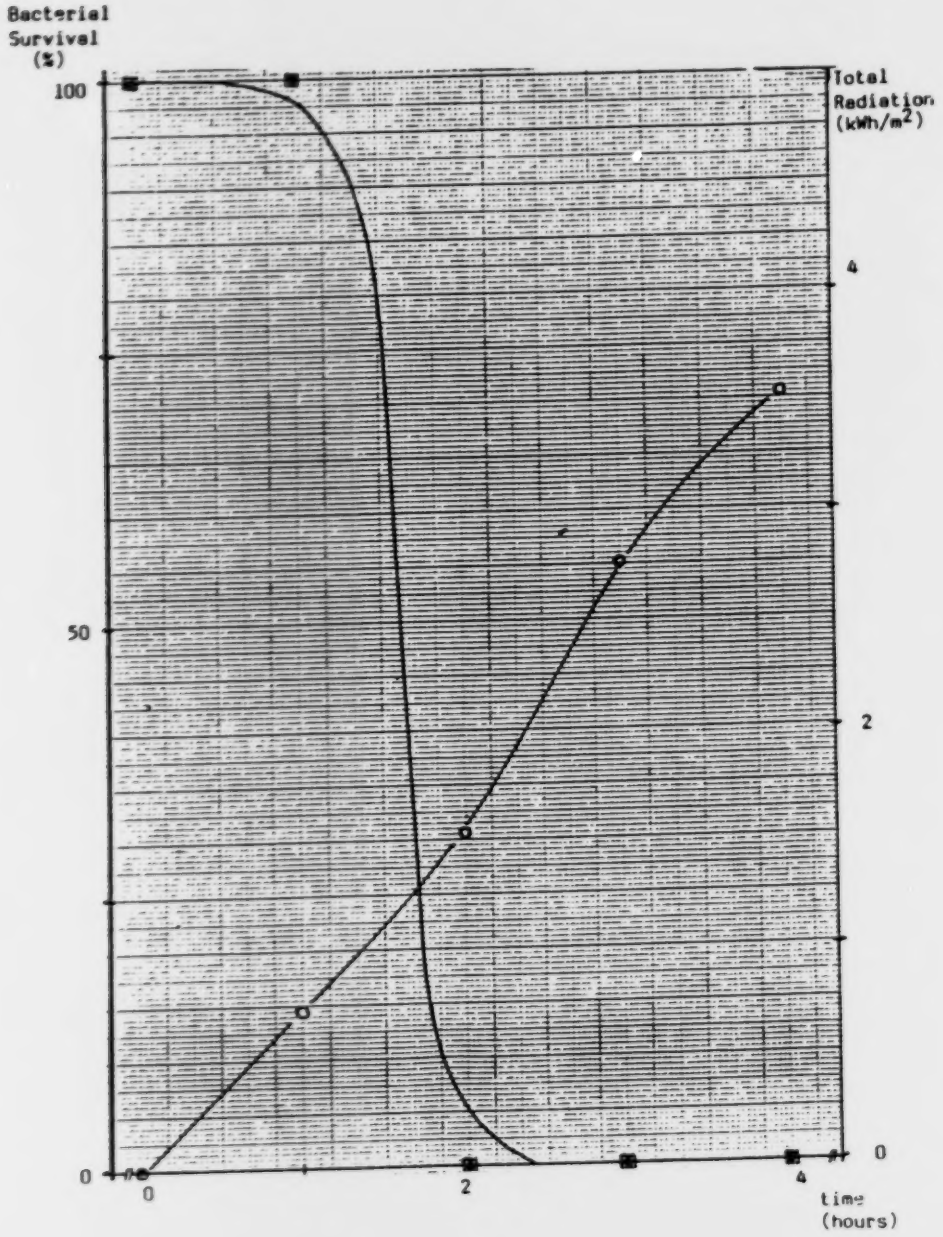

Figure 14. Final inactivation of faecal coliforms previously exposed to brief periods of solar radiation.
(—●—) Bacterial survival after one hour of previous exposure.
(—□—) Bacterial survival after 2.5 hours of previous exposure.
(—○—) Total radiation.
Data from Table 6.

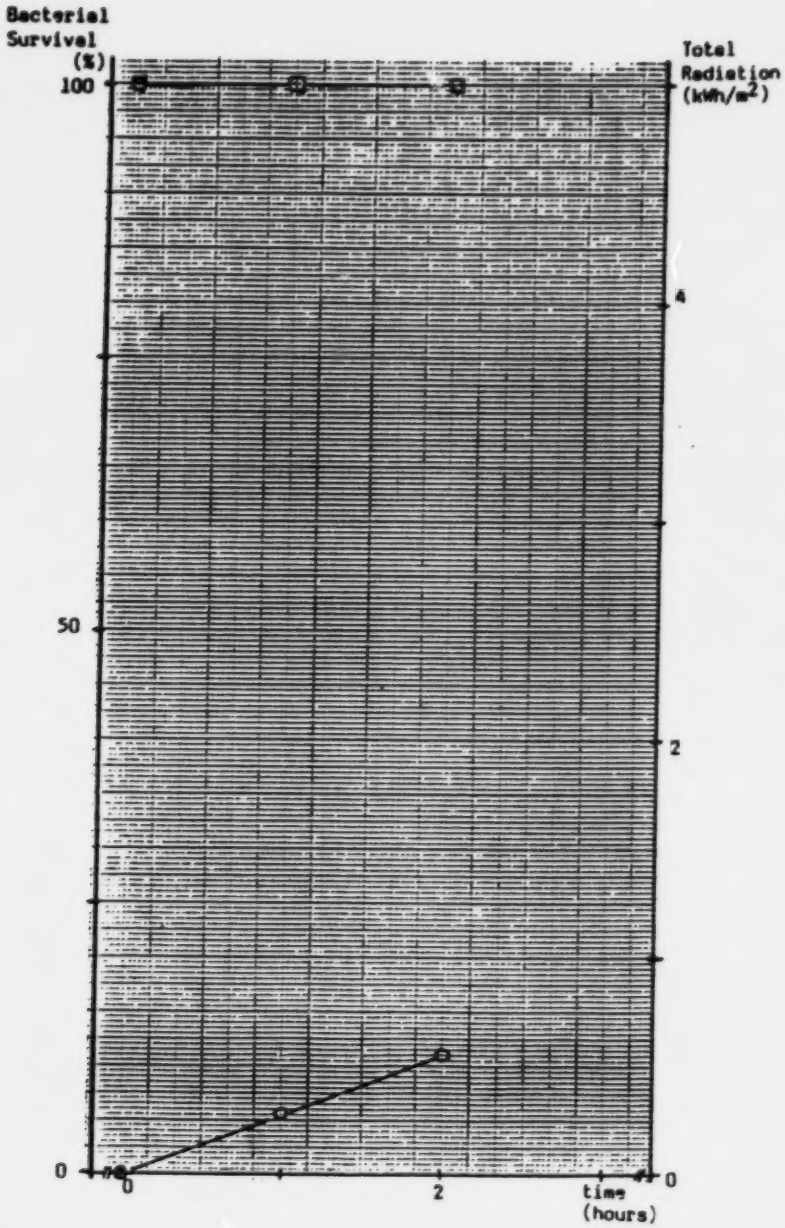

Figure 15. Initial inactivation of total coliforms exposed to low intensity solar radiation for brief periods of time.
(—□—) Bacterial survival. (—○—) Total radiation.
Data from Table 7.

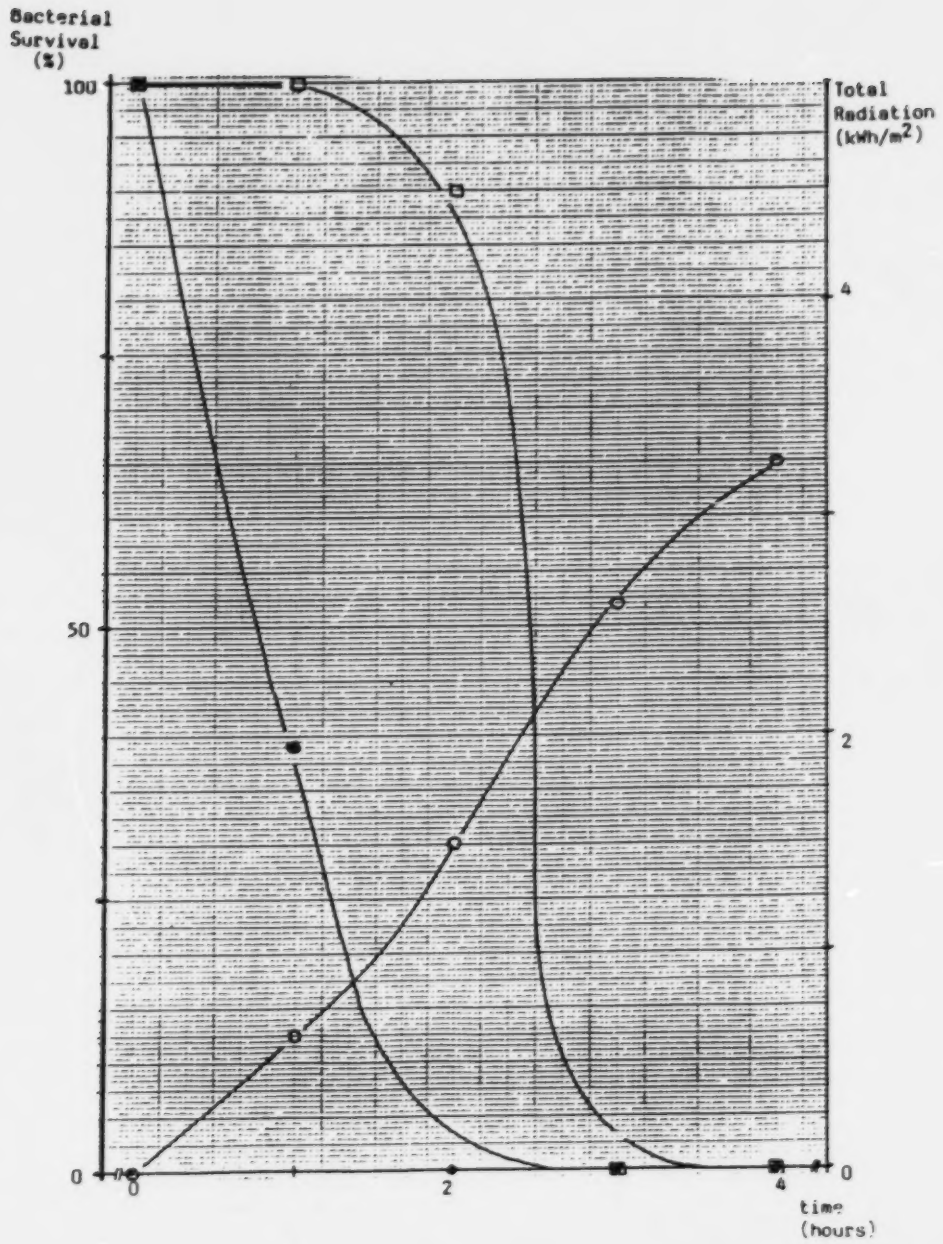

Figure 16. Final inactivation of total coliforms exposed to low intensity solar radiation for brief periods of time.
(-●-) Bacterial survival after one hour of previous exposure.
(-□-) Bacterial survival after two hours of previous exposure.
(-○-) Total radiation.
Data from Table 7.

PHYSICS OF SOLAR WATER DISINFECTION: AN INTRODUCTORY REVIEW

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ABSTRACT

Certain aspects of physics having direct relevance to the recently proposed technique of solar water disinfection are discussed. These include the terrestrial availability of ultraviolet component of solar radiation, transmission of solar radiation through the walls of the containers used, spectral absorption of solar radiation by water and the effect of surrounding surfaces on the availability of solar radiation.

INTRODUCTION

Clean potable water is an essential requirement of human beings. However, as water becomes scarce, people tend to use any locally available source without any form of pretreatment. This leads to the obvious problems of health and sanitation. For example, the high infant mortality rate in most of the developing areas of the world has been found to be caused by the contaminated drinking water in these areas. World Health Organization has estimated that 80% of the world's disease and illness is due to contaminated water [1,2]. It appears that numerous villages around the world will remain without treated water for many years to come and will as a result continue to suffer from many of the water borne diseases unless appropriate techniques for drinking water disinfection are used.

Disinfection of drinking water is a process by which pathogenic (disease producing) organisms are destroyed or otherwise inactivated. Sterilization on the other hand means freeing from all life of any kind. Obviously, disinfection does not necessarily include sterilization, although some processes of disinfection may also accomplish sterilization [3]. Disinfection of water may be accomplished by a number of different physico-chemical treatments including direct applications of thermal energy, ultraviolet, gamma, X and microwave irradiation, ultrasonic disruption and addition of chemical reagents. These approaches, though effective, have their own limitations emerging from technical, social and economic criteria. Chemical treatment has limited scope in poor rural settings with restricted financial capacity, understanding of chemicals (their uses and abuses) and their availability.

Direct application of heat is one of the oldest and most certain methods of water disinfection. Most microorganisms, in an actively growing state are killed by exposure to temperatures of about 70°C for 1 to 5 minutes) [3]. Some are killed in 10 minutes at temperatures as low as 54°C. Commercial pasteurization of milk (63°C for 30 minutes or 72°C for 15 minutes) kills or inactivates all vegetative pathogens in milk including tubercle bacilli (Mycrobacterium tuberculosis). Some vegetative thermophillic cells can

survive 80° to 90°C for as long as 10 minutes. Boiling kills all vegetative microorganisms within 10 minutes. However, this approach, if followed in rural settings of developing areas of the world, is an additional burden on an already strained rural energy economy both at the micro and macro level.

Recently, Prof. A. Acra and his associates at the American University of Beirut in Lebanon have found that exposure of drinking water solutions to a few hours of sunshine in a transparent container would rid the water of enteric bacteria [4,5]. The experiments conducted in this direction in Beirut and elsewhere [4-10] involved exposing small containers of contaminated water to sunlight for varying periods of time. In each case, the water was examined bacteriologically before exposure and at regular intervals of time during exposure to direct sunlight for a certain length of time.

Identical samples of water, in similar containers, kept under room conditions of lighting, and in the dark, served as controls for comparison and assessment. It was found in Beirut, Lebanon that 99.9 % of coliform bacteria were killed by sunlight in 95 minutes, compared with 630 minutes under normal room conditions [5]. Investigations into possible regrowth of the inactivated bacteria after storage have showed that inactivated coliform bacteria fail to regrow after five days under ordinary room conditions. Hence water once disinfected through solar radiation may safely be stored in the home, provided the water does not become recontaminated.

An appropriate technology like solar water disinfection which can eliminate the need for boiling of drinking water prior to its use has great promise in reducing the demand for firewood and/or any other sources of energy. It will not only conserve the fuel already used for boiling of water but would also thwart any future demands of fuel that could arise as people resort to boiled water for health reasons.

The germicidal effect of solar radiation is mainly attributed to its short wavelength component. However, no definitive information is yet available as to which specific wavelengths (or wavelength bands) are responsible for the inactivation/killing of bacteria in water. In addition to the various microbiological aspects of the solar water disinfection process certain issues pertaining to the physics of this apparently simple technology may significantly affect its efficacy. These include the availability and spectral distribution of solar radiation at a specific location, shape, size and the quality of the container used for disinfection, the spectral absorption characteristics of water and the reflection characteristics of surrounding surfaces, etc. This paper presents a brief account of some of these physical processes in view of their role in the solar water disinfection technology.

SOLAR RADIATION : The Ultraviolet Radiation Component

A typical classification of solar radiation according to wavelength is given in Table 1.

Extraterrestrial Solar Radiation:

The energy distribution in the extraterrestrial solar spectrum at the earth's mean distance from the sun is shown in Figure 1 [11]. Table 2 gives the data used in plotting this curve as well as the percentage of the solar constant associated with wavelength shorter than tabulated wavelength [11]. It can be seen from the table that about half of

the sun's energy is concentrated in the visible portion of the spectrum, about 40% is in the infrared and about 10% in the ultraviolet(UV) range, (only about 1% of the energy is in the ultraviolet which is shorter than 2900 A°).

Terrestrial Solar Radiation:

The solar radiation which reaches the earth's surface must pass through the earth's atmosphere. During its passage it is modified by absorption and scattering. Figure 1 also shows the energy distribution in the solar spectrum as observed at the earth's surface (at sea level) [11]. It has been observed that the length of the path traversed by solar radiation also affects the energy received as the air mass increases the energy reaching the earth's surface decreases because of the absorption and scattering in the atmosphere [12]. This effect, however, is not uniform throughout the spectrum and is most marked at the shorter wavelengths. The wavelength corresponding to maximum energy is found to shift from lower to higher wavelengths with increasing airmass. The dependence of the intensity of direct component of terrestrial solar radiation at different wavelengths on the airmass, m can be expressed by the Bouguer-Lambert's law which in its logarithimic form reads [13]:

$$\log I_m = \log I_0 + m \log q$$

where I_0 is the intensity outside the atmosphere, I_m is the intensity after traversing an air mass m and q is the transmissivity of the atmosphere at the particular wavelength.

The absorption in the atmosphere not only cuts off the short-wavc end of the spectrum but also changes the energy distribution radically in the ultraviolet. In space the ratio of intensity at 300 nm to that at 400 nm is about 0.4 while on earth's surface, for airmass one, it is approximately 0.04 [12]. In a recent study, the ratio of intensity at 340 nm to that at 300 nm was found to be 100:1 [14]. These observations indicate that usually on earth's surface, the intensity of near ultraviolet component of solar radiation at ground level will be much more than that of the middle ultraviolet component.

The scattering is provided by small particles present in the atmosphere such as dust and water droplets as well as gas molecules. Each of these particles act as a centre from which radiation is scattered in all directions. If the atmosphere is assumed to be perfectly clean and dry (Rayleigh atmosphere) then the amount of energy scattered by particles much smaller than a wavelength in diameter is inversely proportional to the fourth power of the wavelength. Accordingly, it is expected that the short wavelength portion of the solar radiation will be reduced in intensity by scattering to a greater extent than the visible and infrared portions.

Some analytical and experimental studies are available in the literature which deal with the spectral distribution of solar radiation at the earth's surface, particularly for the middle ultraviolet component of the solar radiation [15-21]. Efforts have also been made to develop instruments to measure the middle ultraviolet radiation component of solar radiation on the surface of the earth [22-25].

The amount of direct solar radiation received by a surface also depends on the angle the sun's rays make with it. Since direct solar radiation reaches the earth in essentially parallel rays, a surface that is perpendicular to their direction of incidence will intercept the greatest amount of energy. As the sun's rays move away from being perpendicular, the

energy intercepted by a surface will decrease. Table 3 presents the variation of the percentage solar interception with the angle of incidence of direct solar radiation on that surface. It may be noted that a surface can be facing as much as 25x away from perpendicular to the sun and still intercept over 90% of direct solar radiation.

Ultraviolet Radiation in the Diffuse Component of Solar Radiation:

The diffuse component of solar radiation also has a significant amount of ultraviolet radiation in it. It may, however, be expected that the spectral composition of diffuse radiation will, in general, differ from that of direct solar radiation.

As discussed earlier, the intensity of the direct component of the terrestrial solar radiation follows the Bouguer-Lambert's law. Since it is not sensitive to the variation of vertical distribution of ozone, aerosols and other atmospheric parameters such as cloud patterns, it is relatively easy to calculate. However this is not the case for the diffuse component. Both the analytical and experimental studies conducted in this area [12,16,26] are limited in their scope due to the fact that in the results of the analytical studies depend sensitively upon the ozone and aerosol models adapted for the computation and the results of the experimental studies are not only site specific but are time dependent as well. Some important results of the above studies are summarized in the following paragraphs which should be considered as typical site specific examples rather than generalized characteristics applicable on a global basis.

Usually, even on a clear day, at certain hours, the amount of ultraviolet radiation in the diffuse component of solar radiation falling on a horizontal surface may be greater than its amount in the direct component. At all other hours of the day, it may at least be comparable in amount with that in the direct component [12]. On a cloudy day the ratio of diffuse to direct component of solar radiation in the ultraviolet region may be more than one [26]. The experimental measurements have also indicated that the ratio of diffuse to direct component of solar radiation in the middle ultraviolet region is generally smaller for measurements made in the morning than those made in the afternoon at corresponding zenith angles [26]. This may probably be attributed to the fact that the aerosol content in the air tends to increase as the day progresses.

The solar altitude also has an appreciable effect on the ratio of diffuse to direct component of solar radiation in the ultraviolet range [12]. During early morning and late afternoons (when the solar altitude is low), the diffuse radiation contribution is nearly four times as much as contribution from direct component.

As regards the seasonal variation in the ratio of diffuse to direct solar radiation, it passes through a minimum at the higher solar elevations, i.e. during the summer months [12]. The diffuse component is relatively large compared with the direct component in winter months. This effect is greatest for the shorter wavelengths. In the 300 nm to 320 nm range the minimum in the curve shifts from June to August. This is because the ratio of diffuse to direct solar radiation(noontime) also depends upon the amount of atmospheric ozone beside the altitude of the sun.

Daily Variation in the amount of UV Component:

The intensity of ultraviolet component of the solar radiation varies throughout the day usually increasing and decreasing with the altitude of the sun [12-14]. The intensity in the

early morning and late afternoon hours is very small compared with that in the middle of the day. For example, during the recently conducted experiments in Beirut, Lebanon, under clear sky conditions the mean values of near ultraviolet days (7-9 October 1983) varied from 5 W/m^2 at 08:35 hours (local time in Beirut) to a peak value of 1105 W/m^2 at 11:45 hours and then gradually receded to 0.7 W/m^2 at 15:55 hours [14]. As mentioned earlier, the greater intensity in the forenoon as compared to that in the afternoon may probably be attributed to the increased turbidity in the afternoon.

The spectral quality of the radiation also varies throughout the day. As the altitude of the sun increases, the ultraviolet component increases much more rapidly than the total solar energy. As a typical example in the measurements made in Washington, D.C., the intensity of ultraviolet radiation shorter than 312.2 nm doubled between 9 and 12 hours while the total solar energy increased by only 7% [12].

Irrespective of the fact that the above details are site specific, general but important conclusions may be drawn so as to make following maximum possible use of solar energy available at a given location for solar water disinfection purposes: (i) the period of exposure of bacterially contaminated water containers to the solar radiation should preferably be centered around the local solar noon; (ii) the diffuse component of the solar radiation may consist of significant amount of ultraviolet radiation and hence should be given appropriate weightage while selecting the containers, site, exposure period, etc.

Geographical Variation:

The spectral quality of solar radiation is not the same at all places, nor is the rate of change in spectral quality the same at all locations [27]. It is difficult to compare observations made at different places by different observers as a wide variety of measurement techniques are used and the spectral ranges covered are also different. It is however suggested that for equal solar elevation the thinner ozone layer in the tropics may result in approximately 15% greater intensity of ultraviolet component [12]. The greater turbidity of the tropical atmosphere on the other hand may reduce the amount of ultraviolet component reaching the earth. The net result is that the intensity of ultraviolet component of solar radiation in tropics is not much different from that in temperate latitudes when the difference in solar elevation is also taken into account. Besides the latitude dependence of the intensity of ultraviolet component of solar radiation, local conditions such as cloudiness, haze, smoke, dust, fog and humidity also affect the intensity in varying degrees.

The elevation above sea level also has a very important effect on the ultraviolet radiation component of solar radiation [12,13]. The direct solar ultraviolet intensity increases with elevation above sea level at constant airmass. This is due to the fact that with increasing elevation the solar radiation traverses a thinner layer of atmosphere, hence reduced absorption. On the other hand the diffuse ultraviolet radiation decreases at higher elevations above the sea level as the lower, more turbid part of the atmosphere is responsible for most of the scattering. The increase in the intensity of the ultraviolet component with the elevation above sea level may be more pronounced in winter as compared to summer values due to the purity of atmosphere at high altitudes during the winter [13].

TRANSMISSION OF SOLAR RADIATION THROUGH WALLS OF THE CONTAINERS

For given solar radiation characteristics, the efficacy of solar water disinfection technique would strongly be affected by the choice of the container particularly the transmittance of its walls for the ultraviolet component of the solar radiation. The quality as well as the quantity of radiation transmitted through the walls of the container is decided by the shape, size and the material of the container besides the altitude of the sun and the spectral distribution of incident solar radiation. This section briefly introduces some of the relevant concepts.

The solar radiation striking a transparent surface may be absorbed by the surface, reflected away from the surface or transmitted through the surface. In other words:

Total incident energy = Absorbed energy + reflected energy + transmitted energy

Whether the energy is absorbed, reflected or transmitted, depends on

i) the wavelength of incident energy
ii) the angle at which the solar radiation strikes the surface
iii) the refractive index of the material and
iv) the absorption coefficient of the material and its thickness

Reflection at the Surface of the Container:

Fresnel's equation sets forth quantatively the amount of light (or incident radiation) reflected at the boundary surface between two transparent media. If I_o is the intensity of a beam of plane polarized light incident at an angle i on the boundary between two media whose refractive indices are n and n^1, and if the beam is plane polarized in the plane of incidence, the ratio of intensity of reflected beam I to the incident beam I_o is given by [9]:

$$I/I_o = \frac{\sin^2(i\, i^1)}{\sin^2(i + i^1)}$$

in which the relationship of i^1 to i is set forth by Snell's law

$$n \sin i = n^1 \sin i^1$$

Similarly, if the incident beam is plane polarized in a plane perpendicular to the plane of incidence

$$I/I_o = \frac{\tan^2(i\, i^1)}{\tan^2(i\, i^1)}$$

Natural or unpolarized light may be assumed to consist of equal amounts of the two components, and the proportions of natural light reflected at the boundary may be expressed as:

$$I/I_o = \frac{\sin^2(i\,i^1)}{2\sin^2(i+i^1)} + \frac{\tan^2(i\,i^1)}{2\tan^2(i+i^1)}$$

It may be noted that for light incident at right angles to the surface and one of the mediums being air (n = 1)

$$I/I_o = (n^1 - 1/n^1 + 1)^2$$

Obviously the reflective losses from the surface of the container are largely dependent on the angle of incidence of the solar radiation on its surface. The greater the angle of incidence, the greater the reflective losses. Another noteworthy point is the simple fact that the reflective losses would increase with the number of interfaces of two different mediums the solar radiation has to penetrate before reaching the water. For example, rest of the conditions being identical the overall reflective losses from the container in Figure 2(b) may be about 3 to 5% higher than that from the container shown in Figure 2(a). This necessitates that the containers should be completely filled with water so as to minimize the number of interfaces.

The angle of incidence of solar radiation on the outer surface of the container would depend on the latitude of the place, season of the year, time of the day and the shape and orientation of the container. Tables 4-7 present the angle of incidence of direct solar radiation on horizontal and south facing vertical surface for four different latitudes.

Absorption in the Walls of the Container:

The overall transmittance of a transparent material is dependent not only on the proportion of the incident light which is reflected, but also on the proportion absorbed in passing through the materiel. If the length of path through the material is L and if this is visualized as divided into a number of layers dL, each of which reduces the intensity I by dI in proportion to the thickness dL and the extinction coefficient K of the sheet, then [28]

$$-dI = I.K.dL$$

Which on integration over the distance between the limits I and the original intensity I_o gives the following expression for the transmittance, (considering absorption only),

$$\tau_a = e^{-KL}$$

Where L is the actual length of path traversed by the beam of light in passing through the sheet of thickness L', and for a given angle of incidence i can be expressed as

$$L = (L'/\cos i)$$

For higher values of angle of incidence of solar radiation on the surface of the container, the path traversed by the solar radiation through the walls of the container will be longer, thus resulting in lower transmittance. Obviously, a container with thicker walls will have a lower transmittance than that of a container of same material with

thinner walls. A preliminary investigation into the wall thicknesses of the commonly available transparent glass and plastic containers indicates that usually the thickness varies from 2 mm to 8 mm for glass containers and from 0.7 mm to 3 mm for plastic containers. Plastic bags of thickness as low as 0.06 mm may also be available in certain areas.

Transmission of Ultraviolet Radiation:

The transmission of glazing materials for ultraviolet radiation is largely determined by the content of iron oxide which absorbs strongly in this region [12,28]. Even small amounts of iron oxide (Fe_2O_3) present as impurities (to the extent of less than 0.01 percent) may have profound effect on the transmission of ultraviolet radiation. Low transmission in the ultraviolet range is usually attributed to the presence of the iron in the ferric condition. The materials most widely used for lamp bulbs which are required to transmit ultraviolet radiation are quartz and various forms of glass. Ordinary window glass in thicknesses of 2 mm or more is practically opaque to ultraviolet radiation of wavelengths shorter than 300 nm [12]. The transmittance of a borosilicate glass, 1 cm in thickness has a value of 0.08 at 310 nm, it rises sharply to 0.65 at 330 nm and attains a peak level of 0.95 to 0.99 from 360 nm to 500 nm [14].

Certain specific glasses transmit significantly more ultraviolet radiation than the ordinary window glass. These include Pyrex, Corex, Vycor and quartz glasses [12]. However, for an appropriate technology like solar water disinfection large scale utilization of these special glasses may not be very attractive due to their high costs and rare availability in the developing areas of the world.

Various types of transparent plastic materials such as Lucite and Plexiglas are good transmitters in the ultraviolet and visible range of solar spectrum [14]. Spectral transmittance curves for some plastics are given in [28]. Their selection would also depend on durability under extreme conditions of exposure, availability and costs. Certain translucent plastics have also been reported to transmit the middle ultraviolet radiation component of solar radiation [29].

ABSORPTION OF SOLAR RADIATION IN WATER

After entering the container the solar radiation is attenuated along its path in the water as a result of absorption and scattering of energy by pure water and suspended and dissolved matter. The overall phenomenon of extinction of solar radiation in water can be described by a wavelength dependent extinction coefficient [30].

$$E_\lambda = K_\lambda + \varepsilon_\lambda + Kw_\lambda + \varepsilon w_\lambda$$

where k and k_w denote absorption of solar radiation of wavelength by pure water and suspended and dissolved matter respectively and ε & εw denote scattering by pure water and by suspended and dissolved matter respectively. Therefore for improving the effectiveness of simple solar water disinfection technology, the turbidity of the water should be reduced to the minimum possible extent prior to its exposure to solar radiation.

The intensity of solar radiation of wavelength at an optical depth X in the water I (λ, X), can be determined by using Beer's law:

$$I(\lambda,X) = I(\lambda,0)e^{-E_\lambda \cdot X}$$

where $I(\lambda,o)$ is the energy in the solar spectrum at the wavelength λ at $X = o$. Several investigators [30-33] have carried out investigations of spectral extinction coefficients mainly for doubly distilled water, pure water and seawater of various origins. Using the values of spectral extinction coefficients given in [33], we have made some simple calculations to determine the transmittance of specific wavelengths of solar radiation passing through water layers of different thickness and the results are given in Table 8. It may be noted from this Table that the ultraviolet component of the solar spectrum can penetrate considerable distance in water with little absorption. It has been reported that up to 10% of the middle ultraviolet component of solar radiation at the surface of clear seawater may penetrate to a depth of 15 m and also that sunlight penetrating to a depth of 4 m in seawater is sufficient to inactivate E. coli [14].

The refraction of solar radiation, as it passes into water, further complicates the calculation of the amount of radiation reaching a given depth of water. If i is the angle of incidence of solar radiation, to reach a depth X, the radiation must travel along an oblique path a distance X' given by [34].

$$X' = X\,(1-(\sin i/n)^2)^{-}$$

Where n is the index of refraction of water for the spectral range under consideration. For an average value of n = 1.35 the ratio (X'/X) equals 1.00, 1.17 and 1.49 for incidence angles equal to 0°, 45°, and 90°, respectively. In other words with an increase in angle of incidence the effective path traversed in water(for a given depth) also increases thus resulting in higher absorption and scattering along the path.

REFLECTION OF SOLAR RADIATION FROM THE SURROUNDING SURFACES ONTO THE CONTAINER

The water container may also receive some direct/diffuse solar radiation contribution from the ground and other surfaces surrounding it (the fraction of the global radiation which is reflected by the receiving surface is termed as its albedo). The amount of this contribution would depend on the nature of solar radiation (direct or diffuse), the surrounding surfaces and the geometrical relationship (view factor) between the positions of the container and the surrounding surfaces. Table 9 presents the surface albedos (averaged over all the wavelengths) for some common surfaces [13]. The percentage reflection of 300 nm ultraviolet radiation from the ground is presented in Table 10 [12]. The rate of solar disinfection of water may, therefore, be increased by a careful selection of the surroundings of the container.

DISCUSSION

Similar to the case of any other emerging renewable energy technology, the solar water disinfection technique is still plagued by a large number of unanswered questions and ambiguities. Many of its facets are yet unexplored and detailed studies are necessary before this technique, which may otherwise have far reaching implications on the well being of the poor in the developing areas of the world, can be put to practical use. The physics of this technology is no exception and rather has a variety of challenges for the

enthusiastic development scientists and engineers. Based on the present status of the technology, some such issues are raised in the following paragraphs along with a few conclusive statements.

i) In view of the fact that the intensity of middle ultraviolet radiation in the terrestrial solar radiation spectrum is very small as compared to the intensity of near ultraviolet radiation, it appears that effectively the near ultraviolet component may be responsible for most of the inactivation/killing of bacteria during the solar water disinfection process [4,8,11,14]. However, the work of several other researchers who have considered the germicidal effect of middle ultraviolet component as well on the natural waters, human bodies, etc. [29, 35-39] merits attention and a careful study. Moreover, it has been reported that the short wavelength portion of the visible spectrum of solar radiation also plays an active role in the process [4]. Future efforts on the physics of solar water disinfection technology should attempt towards a better understanding of the role of solar radiation in the disinfection process and hence a proper identification of the wavelength range(s) of solar spectrum responsible for the inactivation/killing of bacteria.

ii) The characteristics of terrestrial solar radiation at a given location at a certain time of the year would undoubtedly determine the efficacy of the solar water disinfection technology. Given the fact that the establishment of desired number of experimental facilities capable of providing the necessary information in the vast developing areas of the world is not practically feasible, the development of simple models enabling a reliable prediction of the spectral intensity distribution of terrestrial solar radiation at the desired locations using simple site specific environmental indicators is another challenging area.

With a known spectral intensity distribution (within tolerable limits) it would be far more easier to make a preliminary assessment of the feasibility of the solar water disinfection process as well as to take first hand decisions regarding the period of exposure, type of container and its positioning, etc.

iii) The role of the temperature of the water in the container exposed to solar radiation in the solar disinfection process is still debatable. While most of the studies reported so far do not suggest of any significant role played by the water temperature, at this stage one should not neglect the possibility of a temperature supplemented inactivation process. This may be more attractive if a synergetic relationship between the effectiveness of the wavelength of the radiation and the temperature of water could be verified for the simple solar water disinfection process [40]. In such a case, measures such as the blackening of the bottom of the transparent container may be used to enhance the effectiveness of this technology.

iv) For a given volume of water, the amount of solar radiation intercepted by the container will be determined by its shape in addition to the prevailing local solar radiation characteristics. With the limitations of the availability of inexpensive transparent (for ultraviolet and visible component of solar radiation) containers, a careful examination is required to select a suitable container shape. This necessitates a detailed survey of the locally available containers and a thorough evaluation of their solar radiation transmission characteristics.

v) The angle of incidence of solar radiation on the surface of the container has a significant effect on the amount of radiation reaching the water as it affects both the reflection of solar radiation from the surface of the container as well as the absorption of solar radiation in its walls. Moreover, the length of the path traversed by a ray in the water also depends on its angle of incidence larger the angle larger the distance traveled in water to reach a given depth of water. Therefore, depending on the site specific features of the incident solar radiation, efforts should be made to select a container with its shape to minimize the angle of incidence during the operational hours.

vi) A detailed investigation into the spectral absorption characteristics of water is necessary to obtain more reliable information about the depth in water up to which the ultraviolet radiation component can penetrate without appreciable reduction in its intensity. This information may then be used to identify an upper bound on the size (height) of the container.

vii) Another area which merits further attention is the comparative assessment of the solar radiation collection characteristics of horizontal and vertical surfaces. Understandably the result of any such comparative evaluation effort would be site specific and hence necessitate conducting evaluations prior to the experiments so that the containers may be placed accordingly (provided the shape of the container does not pose any practical problems). Carefully undertaken experimental studies are, however, desirable to determine the sensitivity of the results of solar water disinfection process to the shape, size and orientation of the container.

viii) Many other apparently trivial experimental details may affect the efficacy of the solar water purification technique significantly. These include issues such as (i) whether a lid has been used; (ii) whether the container is completely filled with water or has some air gap in it; (iii) whether the outer surface of the container is smooth or rough; (iv) whether the water contains soluble inorganic impurities and suspended particles, etc.

ix) As far as possible, the use of coloured containers should be avoided as they are usually more selective in their solar radiation transmission characteristics as compared to the clear (transparent) containers.

x) With the present understanding of the solar water disinfection process, an identification of a lower bound on the intensity of solar radiation for the practical feasibility of this process does not seem to be a simple task. In fact any such identification (if possible) may need, as inputs, the outcomes of (i), (ii) and (iii), discussed above in addition to the quantitative and qualitative details of the bacterial contamination as well as the envisaged period of exposure to solar radiation.

xi) Further sophistications on the existing simple solar water disinfection technology (such as the use of mirror boosters or solar concentrators etc.) may also be devised. However, it should be remembered that any such effort should not complicate the basic simplicity of this technique to its potential users in the rural areas of the developing countries.

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TABLE 1 CLASSIFICATION OF ELECTROMAGNETIC RADIATION

Wavelength (nm)	Type of radiation
<1	X rays and rays
1-200	Far ultraviolet
200-315	Middle ultraviolet
315-380	Near ultraviolet
380-720	Visible
720-1500	Near infrared
1500-5600	Middle infrared
5600-10000	Far infrared
>10000	Micro and radio waves

TABLE 3 PERCENTAGE OF DIRECT SOLAR RADIATION INTERCEPTED BY A SURFACE AT GIVEN ANGLES OF INCIDENCE

Serial number	Angle of incidence of direct solar radiation (°)	Radiation intercepted (%)
1	0	100.0
2	5	99.6
3	10	98.5
4	15	96.5
5	20	94.0
6	25	90.6
7	30	86.6
8	35	81.9
9	40	76.6
10	45	70.7
11	50	64.3
12	55	57.4
13	60	50.0
14	65	42.3
15	70	34.2
16	75	25.8
17	80	17.4
18	85	8.7
19	90	0

TABLE 2. SPECTRAL DISTRIBUTION OF EXTRATERRESTRIAL SOLAR RADIATION IN THE WAVELENGTH RANGE 290-4000 nm (FROM REF.11). THE FIGURES IN BRACKETS ARE THE VALUES OF THE POWERS OF 10.

Wavelength interval nm ($\lambda_n - \lambda_k$)	*Solar radiation*		
	$W m^{-2}$ *per 0.1 nm*	$W m^{-2}$ *from 0 to* λ_k	% *from 0 to* λ_k
1	2	3	4
290-300	5.24 (-2)	1.57 (+1)	01.156
300-310	6.18 (-2)	2.09 (+1)	01.538
310-320	6.35 (-2)	2.72 (+1)	02.005
320-330	7.81 (-2)	3.50 (+1)	02.580
330-340	9.00 (-2)	4.40 (+1)	03.243
340-350	8.94 (-2)	5.30 (+1)	03.902
350-360	9.49 (-2)	6.25 (+1)	04.601
360-370	10.51 (-2)	7.30 (+1)	05.375
370-380	10.40 (-2)	8.34 (+1)	061.41
380-390	9.45 (-2)	9.28 (+1)	06.836
390-400	11.34 (-2)	1.04 (+2)	07.672
400-410	16.31 (-2)	1.20 (+2)	08.873
410-420	17.00 (-2)	1.37 (+2)	10.125
420-430	16.59 (-2)	1.54 (+2)	11.347
430-440	16.72 (-2)	1.71 (+2)	12.578
440-450	19.28 (-2)	1.90 (+2)	13.998
450-460	20.06 (-2)	2.10 (+2)	15.475
460-470	19.86 (-2)	2.30 (+2)	16.938
470-480	19.89 (-2)	2.50 (+2)	18.403
480-490	18.88 (-2)	2.69 (+2)	19.793
490-500	19.56 (-2)	2.88 (+2)	21.234
500-510	19.02 (-2)	3.07 (+2)	22.635
510-520	18.31 (-2)	3.26 (+2)	23.983
520-530	18.59 (-2)	3.44 (+2)	25.352
530-540	19.17 (-2)	3.63 (+2)	25.764
540-550	18.56 (-2)	3.82 (+2)	28.131
550-560	18.41 (-2)	4.00 (+2)	29.487
560-570	18.28 (-2)	4.19 (+2)	30.833
570-580	18.34 (-2)	4.37 (+2)	32.184
580-590	18.08 (-2)	4.55 (+2)	33.515
590-600	17.63 (-2)	4.73 (+2)	34.814
600-610	17.41 (-2)	4.90 (+2)	36.096
610-620	17.05 (-2)	5.07 (+2)	37.351
620-630	16.58 (-2)	5.24 (+2)	38.583
630-640	16.33 (-2)	5.40 (+2)	39.788
640-650	15.99 (-2)	5.56 (+2)	40.956

TABLE 2. (continued)

Wavelength interval nm ($\lambda_n - \lambda_k$)	Solar radiation		
	$W m^{-2}$ per 0.1 nm	$W m^{-2}$ from 0 to λ_k	% from 0 to λ_k
1	2	3	4
650-660	15.20 (-2)	5.71 (+2)	42.075
660-670	15.55 (-2)	5.87 (+2)	43.220
670-680	15.16 (-2)	6.02 (+2)	44.337
680-690	14.89 (-2)	6.17 (+2)	45.433
690-700	14.50 (-2)	6.31 (+2)	46.501
700-710	14.16 (-2)	6.46 (+2)	47.544
710-720	13.85 (-2)	6.59 (+2)	48.564
720-730	13.56 (-2)	6.73 (+2)	49.562
730-740	13.16 (-2)	6.86 (+2)	50.532
740-750	12.84 (-2)	6.99 (+2)	51.478
750-760	12.65 (-2)	7.12 (+2)	52.409
760-770	12.36 (-2)	7.24 (+2)	53.320
770-780	12.07 (-2)	7.36 (+2)	54.209
780-790	11.83 (-2)	7.48 (+2)	55.080
790-800	11.61 (-2)	7.59 (+2)	55.935
800-810	11.36 (-2)	7.71 (+2)	56.771
810-820	11.04 (-2)	7.82 (+2)	57.585
820-830	10.75 (-2)	7.93 (+2)	58.376
830-840	10.51 (-2)	8.03 (+2)	59.150
840-850	10.06 (-2)	8.13 (+2)	59.891
850-860	9.86 (-2)	8.23 (+2)	60.617
860-870	9.68 (-2)	8.33 (+2)	61.330
870-880	9.47 (-2)	8.42 (+2)	62.028
880-890	9.24 (-2)	8.51 (+2)	62.708
890-900	9.20 (-2)	8.61 (+2)	63.386
900-910	8.98 (-2)	8.70 (+2)	64.047
910-920	8.74 (-2)	8.78 (+2)	64.691
920-930	8.57 (-2)	8.87 (+2)	65.322
930-940	8.41 (-2)	8.95 (+2)	65.941
940-950	8.23 (-2)	9.04 (+2)	66.547
950-960	8.06 (-2)	9.12 (+2)	67.141
960-970	7.89 (-2)	9.20 (+2)	67.722
970-980	7.73 (-2)	9.27 (+2)	68.291
980-990	7.56 (-2)	9.35 (+2)	68.848
990-1000	7.39 (-2)	9.42 (+2)	69.392
1000-1100	6.82 (-2)	1.01 (+3)	74.417
1100-1200	5.58 (-2)	1.07 (+3)	78.530
1200-1300	4.64 (-2)	1.11 (+3)	81.943
1300-1400	3.85 (-2)	1.15 (+3)	84.777
1400-1500	3.23 (-2)	1.18 (+3)	87.154
1500-1600	2.67 (-2)	1.21 (+3)	89.118
1600-1700	2.14 (-2)	1.23 (+3)	90.697
1700-1800	1.75 (-2)	1.25 (+3)	91.983
1800-1900	1.44 (-2)	1.26 (+3)	93.042
1900-2000	1.20 (-2)	1.28 (+3)	93.923
2000-3000	5.53 (-3)	1.33 (+3)	97.998
3000-4000	1.53 (-3)	1.35 (+3)	99.125

TABLE 4 ANGLE OF INCIDENCE (°) ON HORIZONTAL AND VERTICAL SURFACES ON EQUINOXES AND SOLSTICES (LATITUDE = 5°N)

Time of year	Surface orientation[1]	Hours from noon					
		0	1	2	3	4	5
Vernal equinox	H	5.0	15.8	30.4	45.2	60.1	75.1
	V	85.0	85.2	85.7	86.5	87.5	88.7
Summer solstice	H	18.5	23.4	34.3	47.1	60.6	74.3
	V	*	*	*	*	*	*
Autumnal equinox	H	5.6	16.0	30.5	45.3	60.2	75.1
	V	84.4	84.6	85.1	85.9	86.9	88.1
Winter solstice	H	28.4	32.0	40.8	52.3	65.0	78.4
	V	61.6	61.7	62.2	63.1	64.1	65.4

NOTE: *, the surface does not receive direct solar radiation.
[1] H, horizontal; V, south-facing vertical.

TABLE 5 ANGLE OF INCIDENCE ON HORIZONTAL AND VERTICAL SURFACES ON EQUINOXES AND SOLSTICES (LATITUDE = 7.5°N)

Time of year	Surface orientation	Hours from noon					
		0	1	2	3	4	5
Vernal equinox	H	7.5	16.7	30.8	45.9	60.3	75.1
	V	82.5	82.8	83.5	84.7	86.3	88.1
Summer solstice	H	15.9	21.5	32.9	46.0	59.6	73.3
	V	*	*	*	*	*	*
Autumnal equinox	H	8.1	17.0	31.0	45.6	60.4	75.2
	V	81.9	82.2	82.9	84.1	85.7	87.5
Winter solstice	H	30.9	34.2	42.6	53.8	66.2	79.4
	V	59.0	59.3	60.1	61.3	63.0	64.8

NOTE: *, the surface does not receive direct solar radiation.
[1] H, horizontal; V, south-facing vertical.

TABLE 6 ANGLE OF INCIDENCE ON HORIZONTAL AND VERTICAL SURFACES ON EQUINOXES AND SOLSTICES (LATITUDE = 30°N)

Time of year	Surface orientation[1]	Hours from noon					
		0	1	2	3	4	5
Vernal equinox	H	30.0	33.2	41.4	52.2	64.3	77.0
	V	60.0	61.1	64.3	69.3	75.5	82.6
Summer solstice	H	6.6	14.5	27.5	40.5	53.4	66.1
	V	83.4	84.3	87.0	*	*	*
Autumnal equinox	H	30.6	33.8	41.9	52.6	64.7	77.4
	V	59.4	60.5	63.8	68.7	75.0	82.0
Winter solstice	H	53.4	55.4	60.7	68.7	78.6	89.6
	V	36.6	38.0	42.1	48.0	55.0	62.0

NOTE: *, surface does not receive direct solar radiation.
[1] H, horizontal; V, south-facing vertical.

TABLE 7 ANGLE OF INCIDENCE ON HORIZONTAL AND VERTICAL SURFACES ON EQUINOXES AND SOLSTICES (LATITUDE = 45.5°N)

Time of year	Surface orientation[1]	Hours from noon					
		0	1	2	3	4	5
Vernal equinox	H	45.5	47.4	52.6	60.3	69.5	79.5
	V	44.5	46.5	51.9	59.7	69.1	79.4
Summer solstice	H	22.0	25.2	32.8	42.4	52.7	63.2
	V	67.9	69.3	73.2	79.4	87.2	*
Autumnal equinox	H	46.1	48.0	53.2	60.8	69.9	80.0
	V	44.0	45.9	51.3	59.2	68.7	78.9
Winter solstice	H	68.9	70.3	74.2	80.2	87.8	*
	V	21.1	24.4	32.3	42.1	52.7	63.4

NOTE: *, surface does not receive direct solar radiation.
[1] H, horizontal; V, south-facing vertical.

TABLE 8 EFFECT OF SPECTRAL ABSORPTION OF WATER ON THE TRANSMITTANCE OF WATER LAYERS OF VARYING THICKNESSES (cm).

Wavelength (nm)	Absorption coefficient per m	Thickness of water layer					
		10 cm	20 cm	30 cm	40 cm	50 cm	60 cm
310	0.840	.919	.845	.777	.715	.657	.604
313	0.690	.933	.871	.813	.758	.708	.661
320	0.580	.943	.890	.840	.793	.748	.706
330	0.461	.959	.912	.871	.831	.794	.758
340	0.382	.962	.926	.892	.858	.826	.795
350	0.333	.967	.936	.905	.875	.847	.819
360	0.281	.972	.945	.919	.894	.869	.845
370	0.200	.981	.961	.942	.923	.905	.887
380	0.148	.985	.971	.956	.942	.928	.915
390	0.099	.990	.980	.971	.961	.952	.942
400	0.072	.993	.986	.979	.972	.965	.958
410	0.050	.995	.990	.985	.982	.975	.970
420	0.041	.996	.992	.998	.984	.980	.976
430	0.030	.997	.994	.991	.988	.985	.982
440	0.023	.998	.995	.993	.991	.988	.986
450	0.018	.998	.996	.995	.993	.991	.989
460	0.015	.998	.997	.995	.994	.992	.990
470	0.015	.998	.997	.995	.994	.992	.990
480	0.015	.998	.997	.995	.994	.992	.990
490	0.015	.998	.997	.995	.994	.992	.990
500	0.016	.998	.997	.995	.994	.992	.990
510	0.017	.998	.997	.995	.993	.992	.990
520	0.019	.998	.996	.994	.992	.990	.988
530	0.021	.998	.996	.994	.992	.990	.987
540	0.024	.998	.995	.992	.990	.988	.986
550	0.027	.997	.995	.992	.989	.987	.984
560	0.030	.997	.994	.991	.988	.985	.982
570	0.038	.996	.992	.989	.985	.981	.977
580	0.055	.994	.989	.984	.978	.973	.968
590	0.085	.992	.983	.975	.967	.958	.950
600	0.125	.986	.975	.963	.951	.939	.928
610	0.160	.984	.969	.953	.938	.923	.908
620	0.178	.982	.965	.948	.931	.915	.899
630	0.181	.982	.964	.947	.930	.913	.897
640	0.200	.980	.961	.942	.923	.905	.887
650	0.210	.979	.959	.939	.919	.900	.882

TABLE 9 SURFACE ALBEDOS*

Surface	Extremes (%)	Typical mean (%)
Bare soil, stony land	4-25	12
Sand	20-40	30
Cultivated land	10-30	20
Fresh snow	70-90	80
Old snow, ice	30-70	55
Water surface (calm)		
Sun at zenth	3-7	5
Low sun	15-65	20
Clouds	30-85	60
Planet earth		32

* Albedo = the fraction of the global radiation which is reflected by the receiving surface.

TABLE 10 REFLECTION OF 300 nm ULTRAVIOLET RADIATION FROM VARIOUS SURFACES

Surface	Percent Reflection
Fresh snow	85.0
Dry dune sand	17.0
Sandy turf	2.5
Water	5.0

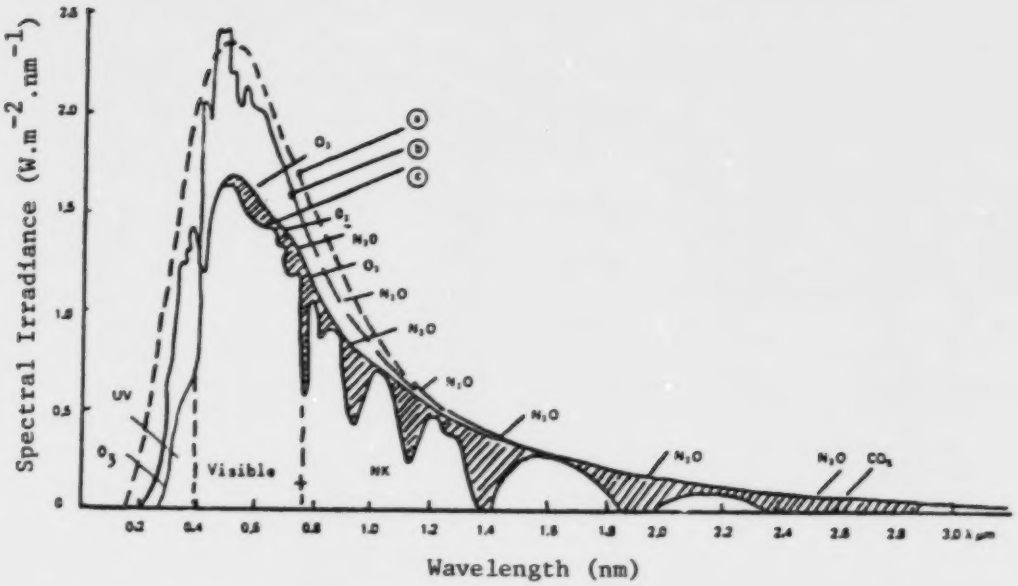

FIGURE 1. SPECTRAL DISTRIBUTION OF (a) RADIATION FROM A BLACK BODY AT A TEMPERATURE OF 6000K (b) EXTRATERRESTRIAL SOLAR RADIATION AND (c) TERRESTRIAL SOLAR RADIATION AT SEA LEVEL.

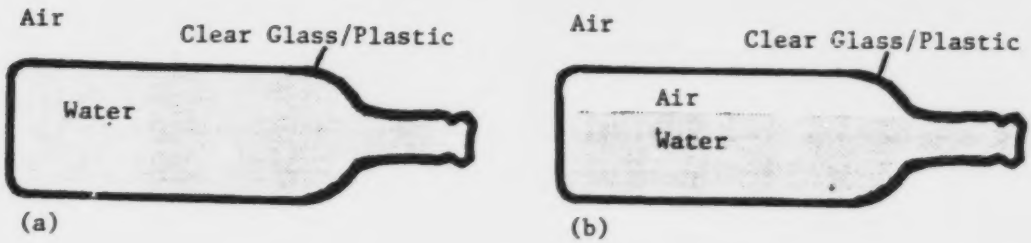

FIGURE 2. TRANSMISSION OF SOLAR RADIATION THROUGH THE WALLS OF THE CONTAINERS

MICROBIOLOGICAL ASPECTS OF SOLAR WATER DISINFECTION

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ABSTRACT

In contrast to the conventional water treatment objective in which the aim is to get rid of the physical, chemical and biological contaminants, solar water disinfection aims only at the solar destruction of biological or microbiological contaminants of the water. To assess the efficacy of sunshine as a water disinfectant series of investigations were conducted in which water samples in transparent containers were exposed to the rays of the sun for varying lengths of time. Control water samples were incubated in complete darkness. Solar radiation was found to exert germicidal effects on coliform bacteria whose population was reduced from 2×10^3/ml to zero within 3 hours of exposure to sunshine during which the sample kept in the dark had its coliform content reduced from 2.5×10^3 to 7×10^2/ml. Coliform bacteria was more susceptible to solar inactivation by sunshine in distilled water than in stream or river water. Bacteria also appeared to be more susceptible to solar inactivation in sterile than in non-sterile water samples. Sewage polluted water was not completely disinfectable by solar energy due to its turbidity bacteria such as Escherichia coli, Salmonella typhi, Staphylococcus aureus and Shigella flexneri were more readily inactivated by solar radiation than the mixed cultures of these organisms. Though the investigation of exposure of the protozoan parasite to solar radiation was not conclusive, nevertheless it appeared that the cysts of Giardia muris might be susceptible to solar inactivation. The period of most rapid decline in bacteria population also coincided with the hours (10:00 to 13:00 hours) of high insolation. The rate of solar destruction of bacteria was similar in both vertically and horizontally positioned water bottles. It is possible to achieve a complete decontamination of a nonturbid water without any fear of bacteria regrowth.

INTRODUCTION

While water remains an essential for life, it serves as a potential reservoir of risk to public health through transmission of diseases to man, animals and fish. Therefore, drinking water must be treated to reduce its potential health risks. The main reasons for treating water supplies are inactivation of pathogenic micro-organisms, removal of iron bacteria which are associated with iron deposits and corrosion of iron pipes, correction of corrosion resulting from acid water, removal or reduction of iron, manganese and colloids, discouragement of scale formation in beating systems, rendering water soft since hard water would not lather easily with soap, and removal of other polluting substances and objectionable matter such as colour, taste, and odour (Mitchell, 1974). To achieve the above objectives, three main stages of sedimentation, filtration and chlorination into an will cover are employed for conventional treatment of drinking water for municipal use. The first two processes of sedimentation and filtration are used principally to get rid of

the abiotic contaminants of the water while chlorination is designed mainly to eliminate the undesirable biotic contaminants.

In the use of solar radiation for water disinfection biotic contaminants are the only targets of elimination as water treatment involves mere exposure of the small scale food processing energy systems of the water sample to sunshine in a transparent container to inactivate potentially pathogenic micro-organisms. Incidentally, of the physical, chemical (abiotic) and biological (biotic) contaminations a stream may experience, biotic especially microbiological contamination is by far the most significant particularly in rural areas. It should be noted that 80% of the sicknesses and diseases in developing countries are caused by water-borne and water-washed diseases, with 25 million people, 60% of whom are children, drying from biologically contaminated water each year (Anon, 1986). Unfortunately it is only the presence of large solids such a faecal material, toilet paper, sanitary towels and animal carcass that provides a visual aesthetic impact indicating water pollution. As micro-organisms are invisible to the naked eye that which cannot be seen in assumed to be absent.

Yet, a large number of these invisible infectious agents are potentially water-borne. Included are viral, bacterial, protozoan, helminthic and mycotic agents in the faecal and urinary wastes of man and lower animals. A list of the micro-organisms involved in excreted infections is shown on Table A. Water-associate diseases can be classified in five ways based on the mode of transmission of the diseases from one person to another. These are water-borne diseases, water-washed diseases, water-based diseases, water-related insect vector-mediated diseases and diseases contacted by eating sea foods (Odeyemi, 1986).

It is not possible to examine a water sample for the presence or absence of all of the disease-causing organisms. Instead, the water is examined for a indicator organism which originates in large numbers from human and animal excreta and whose presence in water is indicative of faecal contamination. Suitable indicator bacterial of faecal pollution are the coliforms especially Escherichia coli and faecal streptococci. It is assumed that if coliforms are found in a water sample, pathogens from the intestinal tracts of infected individuals could be excreted as well. It should be noted that an average adult excretes 2 billion coliforms per day (Mara, 1976). Other supplementary or complementary indicator organisms include Clostridium perfringens, atypical chromogenic mycobacteria and coliphages. For instance, in the Province of Ontario, Canada, a multiple of indicator systems are used rather than coliform alone (Cabelli, 1978). In solar water disinfection studies it important to determine the probable effects of sunshine on both indicator organisms and individual water-borne pathogens.

In the light of the above, the following questions are pertinent with regards to the use of solar energy for water disinfection. Are all water-borne potential infectious agents susceptible to solar inactivation? Are there solar susceptibility differentials among the various groups of aquatic pathogens? For instance, are there interspecific or intra-specific differences among the viral, bacterial, mycotic, protozoan and helminthic pathogens with regards to their solar sensitivity? Which of the water-borne disease agents are more readily inactivated than the others? Do the indicator organisms such as the coliforms readily succumb to solar inactivation? Are individual pure cultures of pathogens more susceptible to solar inactivation than the mixed cultures of the organisms? Is it possible to achieve a complete decontamination of water sample without any danger of pathogen regrowth? What is the quantity or quality of sunshine required to achieve a complete

disinfection of water sample? What is the genetic, biochemical, physiological or photochemical basis of solar inactivation of water-based etiologic agents of diseases?

In this paper, attempts are made to answer some of the questions posed above.

MATERIALS AND METHODS

Methodology of Bacterial Enumeration:

Assessment of bacterial population in this investigation was done by the relatively new Swab and Count technique, which was developed by Double Integral Sanitation Ltd., of Mississauga, Ontario, Canada. The Swab and Count Kit consists of a plain sterile rayon-tipped swab in a plastic polytube filled with 10 ml of sterile phosphate buffer and a dip slide unit with paddle containing two types of media, namely nutrient agar and MacConkey medium with crystal violet. The two media on the paddle allow for a simultaneous enumeration and preliminary differential identification of numerous microorganisms. For instance, the nutrient agar allows for the quantitative estimation of all aerobic microorganisms present in the sample being analyzed, while the MacConkey medium is suitable for the enumeration and detection of coliform bacteria such as Escherichia coli and Klebsiella pneumoniae, and other enteric pathogens like Salmonella and Shigella.

Comparative Evaluation of Swab and Count Technique vis-a-vis the Direct Plate Count:

To determine the relative accuracy of the Swab and Count method, water samples taken from the St.Lawrence River, at Ste Anne de Bellevue, Quebec, were analyzed for total bacteria and coliform content, using the Swab and Count procedure as well as the conventional plate count method. The Swab and Count procedure was carried out as follows. The media paddle of the Swab and Count container was unscrewed carefully and 10 ml of the water sample transferred into the container aseptically. The paddle was then returned to the container which was rotated and swirled for about 30 seconds to ensure that both agar surfaces were covered with the water. The paddle was again carefully removed to discard the remaining water and drain excess fluid from the paddle. The moistened paddle was finally returned to the container and incubated in an upright position at 35°C for 24 to 48 hours. The number of colonies counted on each side of the paddle was then multiplied by a dilution factor of 500 to obtain the approximate number of bacterial/ml of water sample (Double Integral Sanitation Ltd., 1985). The total bacteria and coliform contents of the water sample were also determined by the dilution and plating method, employing nutrient agar to assess total bacteria and MacConkey medium to estimate coliform bacteria.

Effect of Solar Radiation on the Bacterial Load of Sewage Water:

To assess the possible effect of sunshine on the bacterial content of sewage water, samples of raw sewage were collected from the Beaconsfield Sewage Treatment Plant, Beaconsfield, Quebec, and 50 ml each of the sewage added to 500 ml of distilled water contained in 750 ml capacity transparent glass bottles and transparent plastic bottles to make a 10% sewage culture. Four glass and four plastic bottle samples were prepared and two of each sample were put in direct sunshine while the remaining two samples of each treatment were wrapped in a black polythene paper and incubated in a dark cupboard. By

means of a sterile pippete 10 ml of the sewage solution were withdrawn from each bottle and their coliform and total bacteria contents determined at 0, 4, 20, and 24 hours of incubation using the Swab and Count technique.

Vertical vs Horizontal Positioning of Bottles in Sunshine:

To determine if placement of experimental bottles in an upright or flat position during exposure to solar radiation has any effect on the solarcidal activity of the sun's beams, 500 ml of bacteriologically contaminated distilled water were prepared in eight transparent glass bottles. Four of the bottles were then incubated out in direct sunshine with two bottles positioned vertically and the other two placed horizontally. The other four bottles were wrapped with black polythene paper and placed in a dark cupboard horizontally and vertically. Samples were taken at 0, 3, 6, 24 and 30 hours of incubation and analyzed for total and coliform bacteria as described above.

Exposure of Salmonella typhi and Staphylococcus aureus to Solar Radiation:

One millilitre of aqueous suspension of Salmonella typhi strain L and Staphylococcus aureus 1356S (obtained from Dr.E.S.Idziak of the Department of Microbiology, Macdonald College of McGill University, Ste Anne de Bellevue) was added to 500 ml of autoclave-sterilized sample of St.Lawrence River water contained in 750 ml transparent bottle. Six samples were prepared two of which were control samples wrapped with black polythene paper bags and kept in a dark cupboard. The remaining four bottles were put in direct sunshine with two of them covered with black polythene paper bags to determine if the black papers would prevent the rays of the sun from reaching the water to inactivate the bacteria. Samples were taken and analyzed at 0, 3, 6, 24, 27 and 30 hours of incubation after which all the bottles were put in a dark cupboard for three days and again analyzed to check for possible regrowth.

Effect of Sunshine on the Bacterial Density of St.Lawrence River:

Samples of St Lawrence River were taken from Lake St.Louis in Ste Anne de Bellevue, Quebec. Since the lake experiences heavy organic and fecal pollution, 500 ml samples of the water in 750 ml transparent bottles were autoclave-sterilized and 50 ml fresh samples of the river water were added to each bottle. Six bottle samples were prepared and treated as described in the paragraph immediately above. An alcohol-sterilized thermocouple was inserted in each bottle and the thermocouple connected to a datalogger (Digistrip III, Kay Instruments,Inc., Bedford, MA, U.S.A.), that measured and recorded the temperature. As well a pyranometer (Hollis MR5, Hollis Observatory, Nashua, New Hampshire, U.S.A.) was used for measuring solar radiation. Samples for microbiological analysis were taken at 0, 3, 6, 27, and 30 hours of incubation. There was an overnight rainfall till the following morning during the 6th and 27th hour of incubation.

Effect of the Sun's Rays on Shigella flexneri:

Ten millilitres of aqueous suspension of Shigella flexneri LSPQ 2441 (obtained from the Laboratoire de Sante Publique du Quebec, Ste Anne de Bellevue, Quebec) were added to 500 ml of sterile St.Lawrence River water in colourless transparent bottles and green bottles which were subsequently treated exactly as described in the paragraph immediately above.

Exposure of Giardia muris to Solar Radiation

Giardia is a protozoan that causes diarrhoea and malabsorption and a recent report of the WHO placed Giardia amongst the top ten parasites affecting man (Schofield, 1985). An investigation of the possible solarcidal action of the rays of the sun on this pathologically important parasite was carried out in collaboration with Dr.G.M.Faubert and Mr. Wayne Butscher of the Institute of Parasitology, McGill University, Montreal. Laboratory investigation of giardiasis have been facilitated by the availability of the mouse model developed by Roberts-Thomson et al (1976) who reported that oral inoculation of CF-1 Swiss mice with Giardia muris cysts resulted in a reproducible pattern of infection. The Giardia muris used in this study was maintained by 20 day passages through CD-1 Swiss mice in Dr.Faubert's laboratory. The host animals were 6 to 8 weeks old female CD-1 Swiss mice (Canadian Breeding Laboratories, St.Constant, Quebec) which were fed with Purina Lab chow and kept in a group of six animals per cage, bedding changed twice per week and a diurnal cycle of 14 hours light and 10 hours darkness (Belosevic and Faubert, 1983).

Cysts of Giardia muris were collected and extracted from a previously infected set of mice using a modified sucrose gradient centrifugation technique (Roberts-Thomson et al, 1976). To determine the possible effect of solar radiation on the infective cysts, 7,000 cysts were added to 100 ml sterile distilled water in a 250 ml flask. Three flasks were prepared, one was exposed to 8 hours of direct sunshine and another covered with a black plastic bag and kept in the sunlight for 8 hours, the third flask had its cysts isolated and used for oral injection of each of a group of six mice as a zero time control treatment. Each animal was injected with 1000 cysts. After 8 hours of incubation during which temperature and solar radiation values were recorded the cysts of the two flasks were extracted and used to inject each of two separate groups of six animals, one group receiving cysts previously exposed to 8 hours of sunshine, and the other group orally inoculated with cysts subjected to 8 hours of sunshine in a wrapped flask. All the inoculated mice were maintained with adequate food and water as described earlier. Seven days after inoculation with cysts, stools were collected from individual mice over a period of 2 hours, weighed, emulsified in 0.85% saline, layered on sucrose, and centrifuged at 400g for 15 minutes. Cysts concentrated at the saline-sucrose interface were removed, washed in saline, and centrifuged at 600g for 10 minutes. The number of cysts recovered from each sample was then determined by means of a haemocytometer.

RESULTS AND DISCUSSION

Evaluation of Swab and Count Technique:

An estimation of the bacterial density of six samples of St.Lawrence water yielded an average total bacteria population of 4×10^6/ml and a coliform number of 6×10^3/ml, using the conventional plate count method. However, when the same samples were analyzed by the Swab and Count technique, the average total bacteria was 2.5×10^5/ml while the coliform level was 4×10^3/ml. Hence the Swab and Count method was fairly accurate for estimating coliform bacteria but less so for assessing total bacteria since it gave a ten-fold decrease in the theoretical yield of the latter. Since one colony on the Swab and Count paddle represents 500 cells/ml, its margin of error could be relatively high. The dilution factor of 500 inherent in the paddle also means that this technique is

incapable of detecting cell concentrations lower than 500 colony forming units. The Swab and Count method also suffers from an operational problem of water vapours settling on the inside wall of the paddle container during incubation. This excess moisture affects the accuracy of the assay in two ways, it tends to spread bacteria colonies from the nutrient agar portion to the MacConkey medium side (and vice-versa) of the dip slide or paddle; and the unwanted moisture encourages clumping of colonies along the side of the paddle that is in contact with the inner wall of the container. However, it was found that by loosely suspending the paddle (instead of tightly screwing it) inside it's container (thus preventing it from touching the inner wall of the container) and counting bacteria colonies within 24 to 30 hours of incubation rather than after 48 hours, the inaccuracy due to excess moisture could be reduced or eliminated.

Apart from and in spite of the problems of the Swab and Count technique detailed above, the method has important advantages over the cumbersome plate count procedure. For instance it is simple and easy to use, it saves a lot of time, media, materials and labour. It can be used to enumerate both total bacteria and coliform populations of one and the same sample simultaneously. It is fairly accurate especially if the cell concentration is higher than 500/ml.

Bacterial Load of Sewage Water Exposed to Sunshine:

Within 4 hours of exposure to solar radiation the total bacterial density of the 10% sewage water was reduced to 12 and 13% in the glass and plastic bottles respectively, whereas those kept in complete darkness increased to 160 and 100%, respectively (Fig. 1 and Table 1). Similarly, the coliform numbers were reduced to 10% and 16% in the glass and plastic bottle containers while their counterparts kept in complete darkness had 128 and 300% increase in coliform populations, respectively. However, during overnight hours of incubation the total bacteria and coliform populations of the samples kept in complete darkness increased considerably due to abundance of growth supporting nutrients in the sewage.

The nutrients probably acted as a compensating factor to enhance microbial proliferation and thus prevent total solarcidal effect of the sun's rays on the bacteria exposed to radiation, hence the presence of relatively low levels of bacteria in the latter samples even after the second day of exposure to sunlight. The thin-walled plastic bottles seemed to be very slightly more effective than the thicker-walled glass bottles in effecting solar destruction of bacteria probably because the latter container transmitted less radiation than the former.

Vertical vs Horizontal Positioning of Containers:

Coliform bacteria disappeared within 3 hours of exposure to solar radiation in distilled water bottles kept in both upright and flat positions.

Similarly, the total bacteria populations of both samples were reduced by 99.9% after 6 hours of exposure to sunshine. Thus, the vertical or horizontal placement of the experimental bottles seemed to have no influence on the rate of solar destruction of both total and coliform bacteria (Fig. 2 and Table 2).

It should be noted that the period (11-14 hours) of most rapid decline of bacteria population coincided with the recorded hours of relatively high solar intensity.

TABLE 1 EFFECT OF SOLAR RADIATION ON THE TOTAL AND COLIFORM BACTERIA POPULATION OF 10% SEWAGE WATER IN TRANSPARENT GLASS AND PLASTIC CONTAINERS EXPOSED TO DIRECT SUNSHINE AND DARKNESS.

Sample	Hours of exposure			
	0	4	20	24
SI = Sewage sample exposed to sunshine in glass bottle				
Total bacteria/ml	5×10^6	6×10^5	3×10^5	6×10^5
Coliform bacteria/ml	6×10^3	6×10^2	5×10^3	2×10^3
SII = Sewage sample exposed to sunshine in plastic bottle				
Total bacteria/ml	7×10^6	9×10^5	4×10^5	5×10^4
Coliform bacteria/ml	5×10^3	8×10^2	9×10^2	2×10^2
DI = Sewage sample exposed to darkness in glass bottle				
Total bacteria/ml	4×10^6	8×10^6	10×10^6	2×10^7
Coliform bacteria/ml	7×10^3	9×10^3	5×10^4	6×10^4
DII = Sewage sample exposed to darkness in plastic bottle				
Total bacteria/ml	8×10^5	8×10^6	4×10^7	2×10^7
Coliform bacteria/ml	2×10^3	6×10^3	3×10^4	2×10^4

NOTE: SI and SII experienced weak insolation and overnight darkness between 4 and 20 hours of exposure.

The coliform bacteria of the samples kept in complete darkness survived for 6 hours while their total bacteria decreased gradually to 30% and 0.1% by the 24th and 30th hours of incubation, respectively. The gradual and eventual dying out of bacteria in distilled water samples kept in the dark was due probably to the lack or dearth of nutrients in this clarified water.

Solar Decontamination of Water Containing **Salmonella typhi** and **Staphylococcus aureus**:

As can be seen in Fig. 3 and Table 3, both S. typhi and S. aureus died out completely during the first 3 hours (10:00 to 13:00 hours) of exposure of their sterilized river water cultures to sunshine, whereas both organisms persisted for more than 24 hours in the water bottles wrapped in black polythene bag and also kept in the sunshine. It should be noted though that there was also a rapid decline in the bacteria density of the latter samples. Since the black plastic wrapper absorbed the solar radiation thus preventing it from being transmitted to the bacterial cells to inactivate them, it could be inferred from this observation that solar radiation played a significant role

TABLE 2 EFFECT OF SOLAR RADIATION ON THE COLIFORM BACTERIA AND TOTAL BACTERIA DENSITY IN DISTILLED WATER CONTAINED IN GLASS BOTTLES PLACED VERTICALLY AND HORIZONTALLY IN SUNSHINE AND DARKNESS.

Sample	Hours of exposure				
	0	4	20	24	30
SI = vertically in sunshine					
Total bacteria/ml	6×10^4	5×10^3	6×10^2	0	0
Coliform/ml	5×10^2	0	0	0	0
SII = horizontally in sunshine					
Total bacteria/ml	3×10^4	5×10^3	7×10^2	0	0
Coliform/ml	6×10^2	0	0	0	0
DI = vertically in complete darkness					
Total bacteria/ml	2×10^4	9×10^3	8×10^3	6×10^3	0
Coliform/ml	9×10^2	6×10^2	5×10^2	0	0
DII = horizontally in complete darkness					
Total bacteria/ml	2×10^4	8×10^3	7×10^3	6×10^3	0
Coliform/ml	8×10^2	5×10^2	4×10^2	0	0

NOTE: SI and SII experienced weak insolation and overnight darkness between 6 and 24 hours of exposure.

in the demise of bacteria exposed directly to the sun's rays. The peak of insolation corresponded with the period of rapid decline in bacterial population. It is important to note also that there was no bacterial regrowth in the samples exposed directly to sunshine during the three day post-incubation period of keeping these samples in darkness. On the other hand, the wrapped samples kept in sunshine were not completely disinfected since there was bacterial regrowth in those samples during the three days of being kept in darkness (Table 3). The relatively low numbers of bacteria in the latter samples were detected by the membrane filter and plate count techniques since the Swab and Count method is inherently incapable of detecting such low numbers.

Effect of Sunshine on the Bacterial Load of St.Lawrence River Water:

There was a seemingly rapid decline of total bacteria and coliform populations to 8% and 0.1% respectively during the first 3 hours (10-13 hours) of exposing the diluted St.Lawrence River water to solar radiation. During the same period the total bacteria and coliform densities of the sunshine-exposed wrapped samples decreased by 86% and 50%

TABLE 3 EFFECT OF SUNSHINE ON WATER CULTURES (BACTERIA/ml) OF Salmonella typhi STRAIN L AND Staphylococcus aureus STRAIN 1356S EXPOSED TO THE SUN'S RAYS IN TRANSPARENT 750-ml GLASS BOTTLES.

	Hours of exposure					Post-incubation hours		
Sample[1]	0	3	6	24	30	24*	48*	72*
S (St + Sa)	1.8 x 10	0	0	0	0	0	0	0
S (Sa)	5 x 10	0	0	0	0	0	0	0
D (St + Sa)	1.8 x 10	3 x 10	5 x 10	6 x 10	1 x 10	5	10	8
D (Sa)	4.5 x 10	1.5 x 10	5 x 10	3.5 x 10	0	2	3	1

[1] S = 1 ml aqueous suspension of S.typhi strain L + S aureus strain 1356S added to 500 ml of sterilized river (St.Lawrence) water in a transparent bottle exposed to direct sunshine. D = sample treated as in (S) above but wrapped in black polythene paper and also kept in direct sunshine adjacent to bottle (S). Sa = S. typhi. St = S. aureus. Note that samples S and D experienced weak sunlight and overnight darkness between 6 and 24 hours of exposure.

[2] Post-incubation hours (in the dark) to determine possible regrowth.

respectively, while those of the bottles kept in complete darkness decreased by 40% and 70%, respectively (Fig. 4 and Table 4). However, by the 6th hour of incubation both total bacteria and coliform populations of the wrapped-in-the-sun samples increased considerably probably due to the relative increase in temperature (Fig. 5), whereas the total bacteria of the sample exposed to direct sunshine decreased to about 4%. This observation suggests again that solar radiation rather than temperature played a role in the disappearance of bacteria exposed to sunshine. It is interesting to note that during this particular experiment there was a fairly heavy overnight rainfall with cloud cover that lasted till late the following morning, after which the bacteria numbers of all the samples increased exponentially. Even the coliform bacteria that had disappeared during the first 3 hours of direct exposure to sunshine regrew during the overnight period of rainfall and morning overcast. Barring contamination and lack of sunshine, the reasons for this surge in bacterial density is not understood. It is noteworthy too that the water temperatures of both wrapped and unprotected bottles exposed to sunshine were consistently higher than the corresponding ambient air temperatures (Fig. 5).

TABLE 4 CHANGES IN BACTERIAL DENSITY (PER ml) UPON EXPOSURE OF SAMPLES OF ST LAWRENCE RIVER WATER (STE ANNE DE BELLEVUE) TO SUNLIGHT.

Sample	Hours of exposure					
	0	3	6[1]	24	27	30
SI = 50 ml of river sample added to 500 ml of sterile river water in a transparent bottle exposed to direct sunshine.						
Total bacteria	1.2 x 10	1.0 x 10	4.5 x 10		3.0 x 10	2.0 x 10
Coliform	2 x 10	0	0		7.5 x 10	9.0 x 10
SII = Sample treated as in S but with the bottle wrapped up in a black polythene paper prior to exposure to sunlight.						
Total bacteria	1.1 x 10	1.5 x 10	3.3 x 10		9.0 x 10	8.0 x 10
Coliform	1.0 x 10	5 x 10	1.5 x 10		3 x 10	3.3 x 10
DI = Sample treated as in S but with the bottle wrapped up in a black polythene paper and put in a dark cupboard.						
Total bacteria	1.0 x 10	6 x 10	3.5 x 10		8.0 x 10	7.5 x 10
Coliform	2.5 x 10	7.0 x 10	5.0 x 10		2.5 x 10	2.1 x 10

[1] SI and SII experienced weak radiation and overnight darkness between 6 and 24 hours of incubation.

Transparent Bottles vs Green Bottles:

The rates of total bacteria and coliform decline in both transparent and green waterbottles were similar especially during the first 6 hours (10:00 to 14:00 hours) of exposure to sunshine, suggesting that the solar destruction of the organisms was not influenced by the colour of the containers (Fig. 6 and Table 5). It must be noted however, that there was considerable overcast coupled with low ambient air temperatures during the period of this investigation (Fig. 7). The small amount of diffuse radiation probably only served to encourage bacterial survival and multiplication especially during the 24th to 30th hours of incubation when there was a slight increase in ambient temperature. However, it is not understood why the coliform bacteria of samples kept in total darkness died out during this period. Hence the low temperatures, weak insolation, and significant cloud cover made it difficult to differentiate the treatment effects between the colourless transparent bottles and the dark green bottles. Theoretically, the iron colourant of the green bottle is supposed to absorb much of the ultraviolet radiation which is assumed responsible for the germicidal action of the sunshine, thus rendering it less effective than the transparent bottle (Acra et al., 1984). The amount of radiation transmitted through a container depends on the following four factors: (a) colour of the

TABLE 5 EFFECT OF SUNSHINE ON THE BACTERIAL LOAD (PER ml) OF ST LAWRENCE RIVER (STE ANNE DE BELLEVUE) WATER SAMPLES, EXPOSED TO SOLAR RADIATION IN COLOURED (GREEN) AND COLOURLESS BOTTLES.

Sample	Hours of exposure					
	0	3	6*	24	27	30
S_T = 25 ml of river water sample added to 500 ml of sterile river water in a transparent bottle exposed to direct sunshine.						
Total bacteria	8.5 x 10	9.5 x 10	1.0 x 10	5.0 x 10	4.0 x 10	9.0 x 10
Coliform	1.0 x 10	5.0 x 10	5.0 x 10	1.0 x 10	5.0 x 10	1.0 x 10
S_G = 25 ml of river water sample added to 500 ml of sterile river water in a green bottle exposed to direct sunshine.						
Total bacteria	7.6 x 10	9.0 x 10	5.0 x 10	7.5 x 10	1.1 x 10	1.8 x 10
Coliform	2.0 x 10	8 x 10	5.0 x 10	7.0 x 10	3.5 x 10	8.0 x 10
D_G = 25 ml of river water sample added to 500 ml of sterile river water in a green bottle wrapped in a black polythene paper and kept in the dark.						
Total bacteria	8.5 x 10	4.0 x 10	2.5 x 10	1.1 x 10	7.0 x 10	2.3 x 10
Coliform	4.0 x 10	2.0 x 10	5.0 x 10	1.5 x 10	0	0

NOTE: S_T and S_G experienced poor insolation and overnight darkness between 6 and 24 hours of exposure.

container, (b) wall-thickness of the bottle, (c) refractive index of the container, and (d) spectrum of the incident radiation (Cotis, 1986).

Effect of Solar Radiation on **Shigella flexneri**:

During the first 3 hours (10:00 to 13:00 hours) of exposure to sunshine, the numbers of S. flexneri reduced to 43% in the transparent bottles and 60% in the green bottles whereas the population rose to 125% in the water bottles incubated in total darkness (Fig. 8 and Table 6), thus suggesting bactericidal effect of sunshine in the former bottles. The water temperature of the bottle kept in the dark was relatively stable at about 18.5°C during the day and in the night, whereas those of the other bottles were relatively high during the day and low during the night (Fig. 9). The water temperature of the transparent bottle was also relatively higher than that of the green bottle exposed to sunshine. Hence there was a slight treatment effect between the colourless and the green bottles, as the bacterial population of the former decreased slightly more than that of the latter, thus suggesting that transparent containers are more efficient than green containers in transmission of radiation and hence effecting solar destruction of water bacterial contaminants.

TABLE 6 INFLUENCE OF SOLAR RADIATION ON A WATER SUSPENSION OF Shigella flexneri LSPQ 2441 EXPOSED TO THE SUN'S RAYS IN TRANSPARENT AND GREEN BOTTLES.

Sample[1]	Hours of exposure					
	0	3	6*	24	27	30
S_T	8.2 x 10	3.5 x 10	5.0 x 10	7.5 x 10	5.0 x 10	4.0 x 10
S_G	8.3 x 10	5.0 x 10	9.0 x 10	3.5 x 10	3.0 x 10	1.0 x 10
D_G	8.0 x 10	1.0 x 10	5.0 x 10	7.5 x 10	8.0 x 10	7.5 x 10

NOTE: S_T and S_G experienced weak sunlight and overnight darkness between 6 and 24 hours of exposure.

[1] S_T = 10 ml of water suspension of S. flexneri LSPQ added to 500 ml of sterile St Lawrence River water in a transparent bottle exposed to direct sunshine. S_G = 10 ml of water suspension of S. flexneri LSPQ added to 500 ml of of sterile St Lawrence River water in a green bottle exposed to direct solar radiation. D_G = 10 ml aqueous suspension of S. flexneri LSPQ added to 500 ml of sterile St Lawrence River water in a green bottle wrapped in a black polythene paper and incubated in the dark.

Exposure of a Protozoan Parasite to Solar Radiation:

As shown in Table 7, none of the cysts exposed to solar radiation was infective on the CD-1 Swiss mice thus suggesting probable solar destruction of the parasites in the water bottles. Coincidentally, there was a high degree of insolation especially during the first 5 hours of the experiment (Fig. 10). It should be noted too that the water temperatures in both transparent and wrapped bottles were considerably higher than the ambient air temperature. However, the experiment was deemed inconclusive because only a third of the control Group A (Table 7) mice were infected when inoculated with the cysts that were not exposed to sunshine. When the experiment was repeated, similar inconclusive results were obtained. The inconclusiveness of this particular investigation might have been due to infectivity problems of the mice, or osmotic shock of cysts in distilled water, or cyst extraction difficulty. Unfortunately the constraints of both time and weather did not allow a proper validation of this important investigation. As mentioned earlier, Giardia is one of the top ten parasites affecting man. Giardiasis is also the most frequently diagnosed parasitic infection of humans in Canada and the U.S.A. (Notifiable Diseases Summary, 1985) where several outbreaks have been reported in the cities especially in the Rockies (Weniger et al; 1983). The infection in man is transmitted through the fecal-oral route and frequently through contaminated drinking water (Owen, 1984). The parasite has been reported not to be readily susceptible to the conventional chlorination method of inactivating drinking water pathogens (Jarrol et al; 1981). Hence the susceptibility of Giardia to solar destruction would be of considerable significance.

TABLE 7 AN ASSESSMENT OF POSSIBLE MICE INFECTION BY THE CYSTS OF Giardia muris BEFORE AND AFTER EXPOSURE TO SOLAR RADIATION.

Mouse no.[1]	Wt. of feces	Cysts/ml	Cysts/g
A1	0.21	1.82×10^6	8.67×10^6
A2	0.18	6.7×10^5	3.7×10^4
A3	0.25	0	0
A4	0.40	0	0
A5	0.18	0	0
A6	0.12	0	0
B7	0.22	0	0
B8	0.17	0	0
B9	0.16	0	0
B10	0.18	0	0
B11	0.21	0	0
B12	0.12	0	0
C13	0.13	0	0
C14	0.36	0	0
C15	0.34	0	0
C16	0.22	0	0
C17	0.15	0	0
C18	0.30	0	0

[1] Group A mice were each injected with 1000 cysts of G. muris that had not been exposed to solar radiation i.e. at time zero. Group B mice were each injected with cysts of G. muris that had been exposed to 8 hours (10-16 hours) of sunshine. Group C mice were each inoculated with cysts of G. muris extracted from water bottles exposed to 8 hours of sunshine in a dark plastic wrapper.

SUMMARY AND CONCLUSIONS

Despite the poor weather and other constraints experienced during this investigation, the tentative findings can be summarized as follows:

a) Solar radiation seems to exert germicidal effects on coliform bacteria and also on total bacteria populations, with the former being more susceptible than the latter (Table 4).

b) Bactericidal action of solar radiation may take only 3 hours on a clear sunny day or several hours on a cold cloudy day.

c) Bacteria seem to be more rapidly inactivated by solar radiation in distilled water than in stream or river water due to the presence of suspended particles in the latter (Figs.2 & 3). Bacteria also appear to be more susceptible to solar inactivation in autoclave-sterilized river water than in non-sterile water.

d) Sewage water may not be completely disinfectable by solar radiation because of its high turbidity which can exert attenuating effects on the transmission of the rays of the sun, and also due to the presence of nutritive elements in the sullage, thus encouraging microbial proliferation (Fig. 1). Therefore, sewage or any turbid water samples should be clarified e.g. by filteration through charcoal, clay or sand, prior to exposure to sunshine in order to achieve a reliable solar decontamination (Odeyemi, 1986).

e) Individual pure cultures of bacteria such as E. coli, S.Typhi, S. aureus and S. flexneri appear to be more readily inactivated by solar radiation than the mixed cultures of organisms.

f) The period of most rapid decline in bacteria population also coincides with the hours (10:00 to 13:00 hours) of high insolation in most of the cases (Figs.3 & 4). Hence it is advisable to expose contaminated water samples to sunshine during the predetermined hours of high insolation which is generally between 10:00 and 14:00 hours.

g) It is possible to achieve a complete decontamination of a fairly clarified water without any danger of bacteria regrowth (Table 3), if the disinfected water is properly stored.

h) An improperly disinfected water may have substantial increase in its bacterial density during overnight storage, i.e. the morning after (Fig. 4, Tables 4 & 5). Therefore, in areas or periods of low solar intensity, it is advisable to expose water samples to sunshine for several hours or days prior to consumption.

i) It seems also that the vertical or horizontal positioning of water bottles exerts no influence on the rate of solar destruction of bacteria (Fig. 2 & Table 2).

k) Solar radiation rather than temperature seems to play a key role in the demise of bacteria in water samples exposed to sunshine (Fig. 3 & Table 3, Fig. 4 & Table 4). In fact the highest water temperature recorded throughout the period of this investigation was 38°C on 14 August, 1986 (Fig. 5), which is far below the thermal death points of most bacteria except psychrophiles. Cotis (1986) also reported that a water temperature of 39°C has no effect on the bactericidal action of solar radiation. It should be noted though that the temperature of the water samples exposed to sunshine (highest 38°C) was consistently higher than the ambient air temperature (highest 28.5°C) (Fig. 5).

l) Though the investigation of exposure of the protozoan parasite to solar radiation was not conclusive, nevertheless it appears that the cysts of Giardia muris may be susceptible to solar inactivation. Further studies are necessary to confirm this observation.

m) The Swab and Count technique appears to be a fairly accurate and reasonably suitable method of assessing solar disinfection of drinking water mainly because of its rapidity and also because of its relative sensitivity, ease of use, simplicity, time and labour saving. The method seems to be more suitable for evaluating coliform bacteria, which incidentally are the indicators of fecal pollution of water, than for enumerating total bacteria. It should be mentioned also that the technique is

recommended by Double Integral Sanitation Ltd., for detecting and identifying many contaminating microorganisms found in the pharmaceutical, hospital, restaurant, food and dairy industries.

In conclusion, it should be mentioned that complete decontamination of water samples was not achieved in many of the cases investigated because of weak and diffuse solar radiation and low ambient temperatures during the period of the study. For instance, the only time when there were five straight days of sunshine was from 16 to 20 August, 1986. Most of the summer was characterized by considerable cloud coverage, incessant rainfall, and high humidity. Of course, Montreal, Canada, lies on latitude 45°N, an area that experiences a relatively low insolation due to frequent and extensive cloud cover which exerts diffusional and attenuating effects on the radiation (Acra et al.,1984, Odeyemi, 1986). Fortunately however, most of the developing countries of the world lie between latitudes 35°N and 35°S, where solar radiation is very high, with some areas receiving about 3,000 sunshine hours per year. This type of investigation should therefore be carried out in such areas of bountiful sunshine where most of the peasants who are expected to benefit from solar disinfection of drinking water, have their abode.

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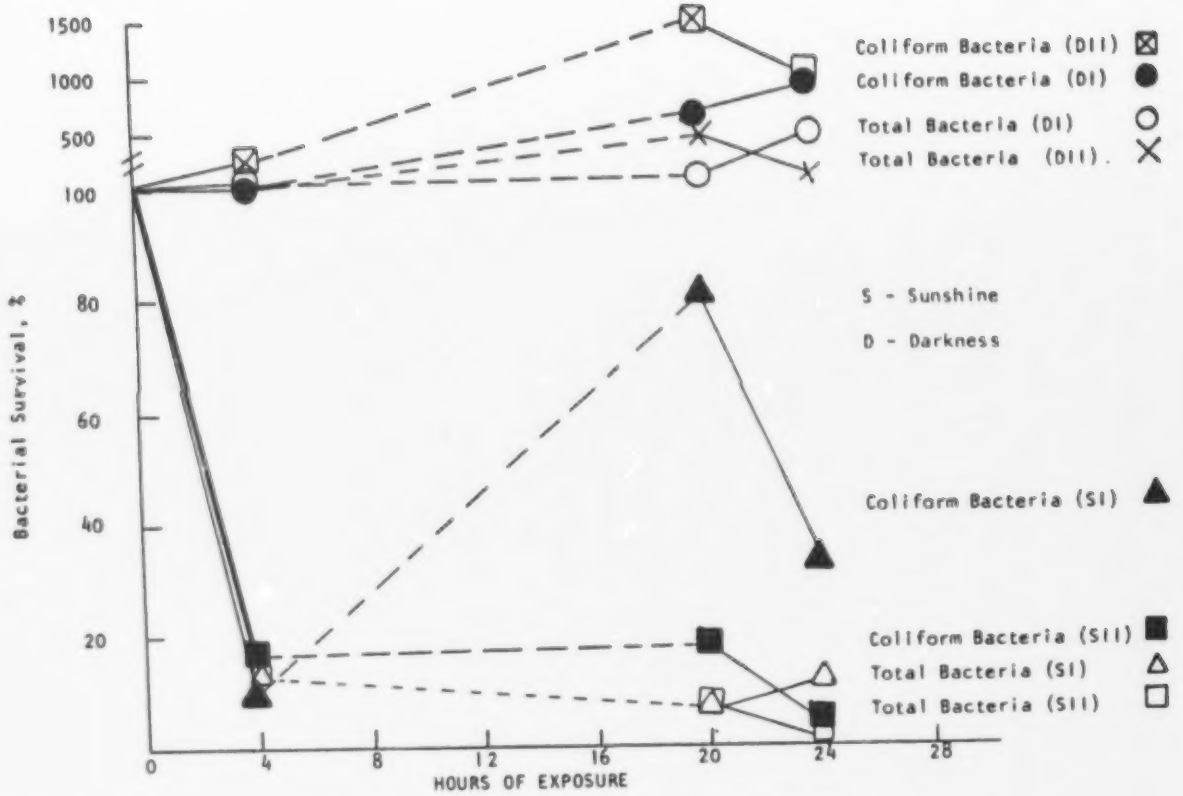

FIGURE 1. Effect of solar radiation on the total and coliform bacteria populations of 10% sewage water in transparent and plastic containers exposed to some hours of sunshine.

NOTE: In this and subsequent Figures, broken lines indicate incubation periods/hours, of low insolation plus overnight darkness when measurements were not made.

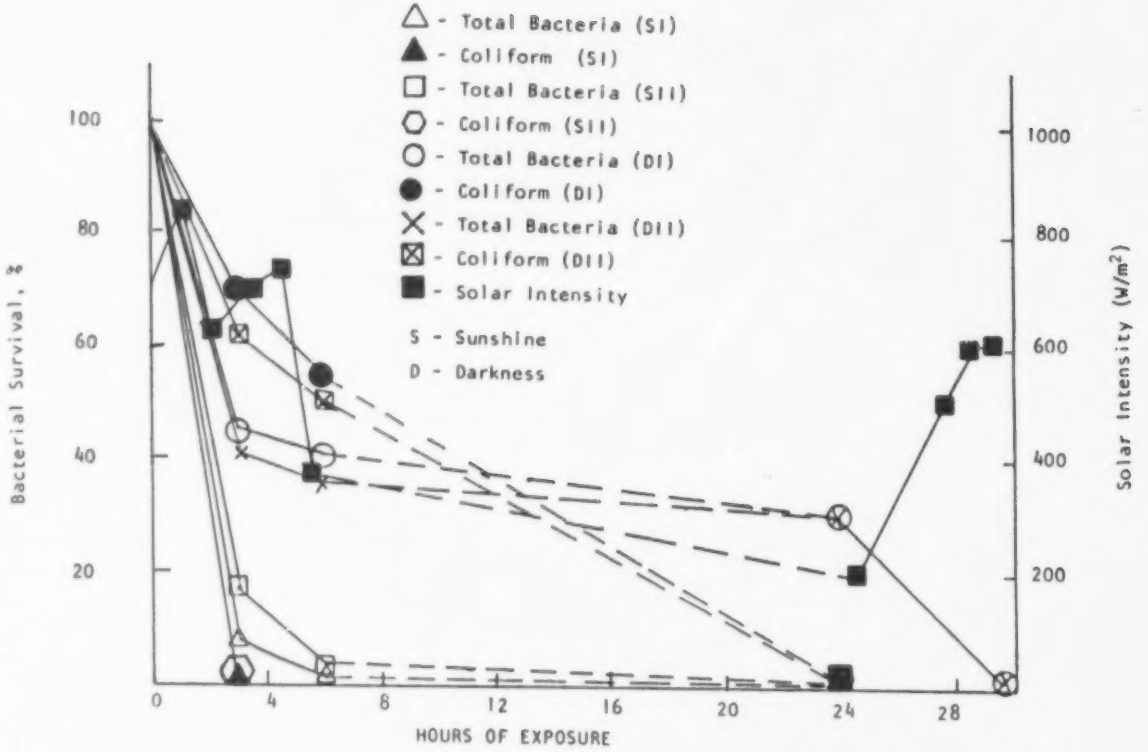

FIGURE 2. Effect of solar radiation on coliform and total bacteria density of contaminated distilled water contained in glass bottles placed vertically and horizontally in sunshine.

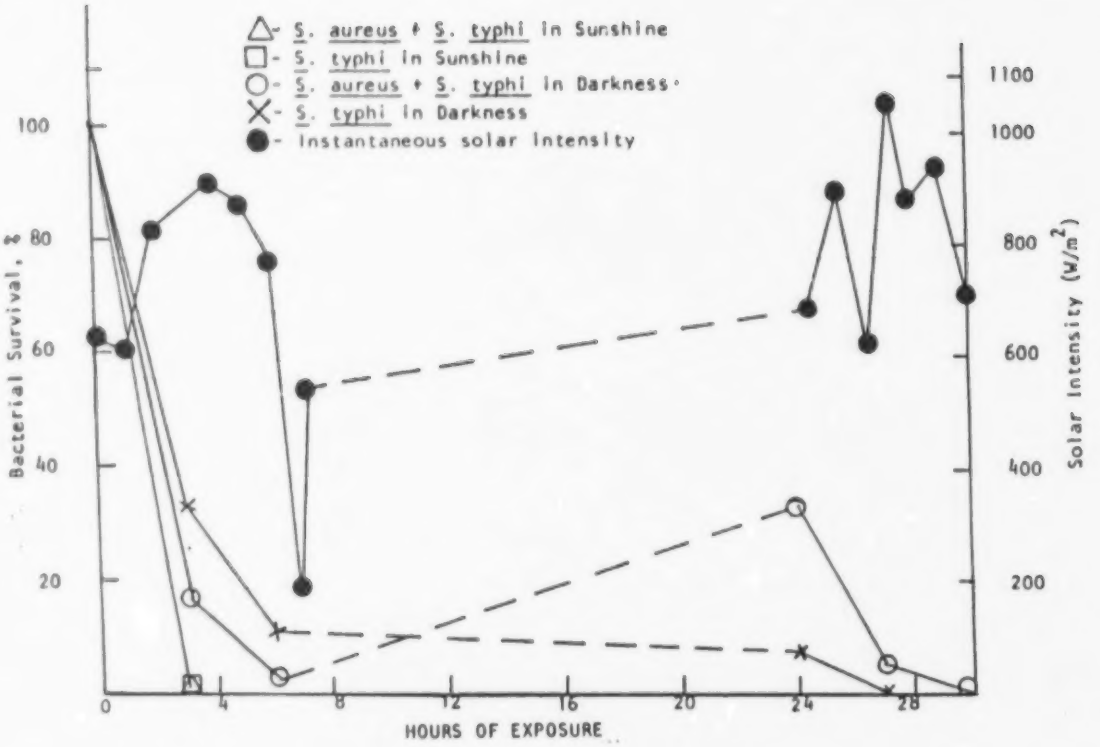

FIGURE 3. Rapid decline of populations of Salmonella typhi and Staphylococcus aureus in water samples exposed to the sun's rays in a transparent glass bottle.

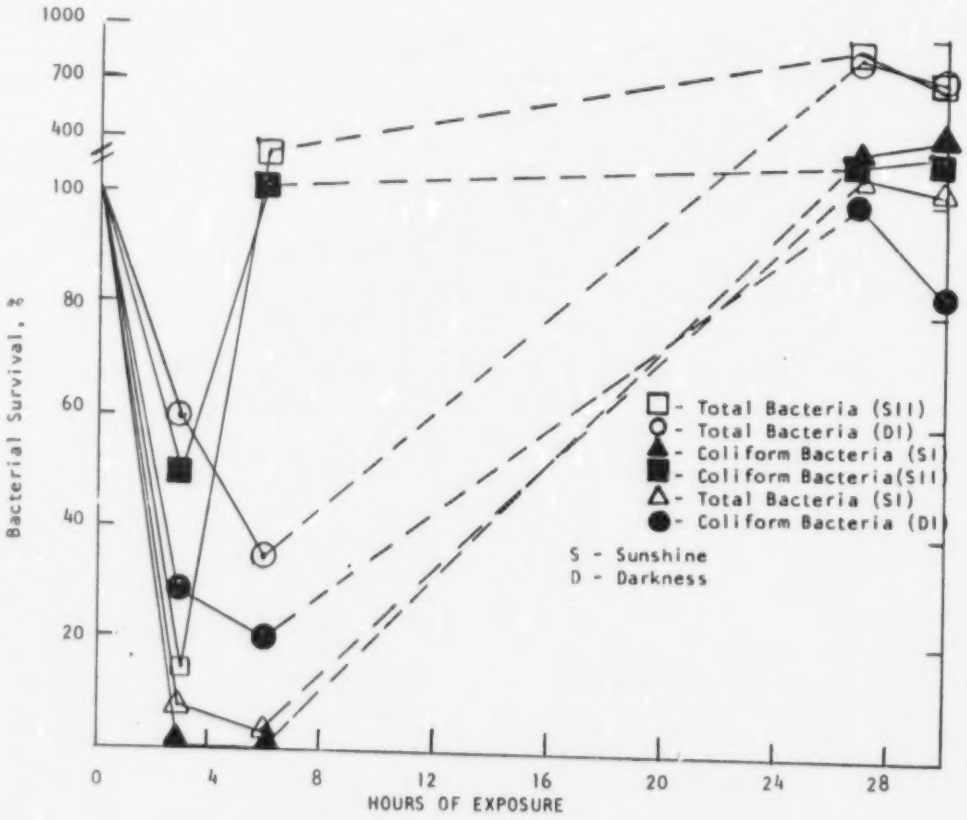

FIGURE 4. Changes in bacterial density upon exposure of samples of St.Lawrence River to sunlight in a transparent bottle (SI) and a black plastic-wrapped bottle (SII), compared to the bottle in darkness (DI).

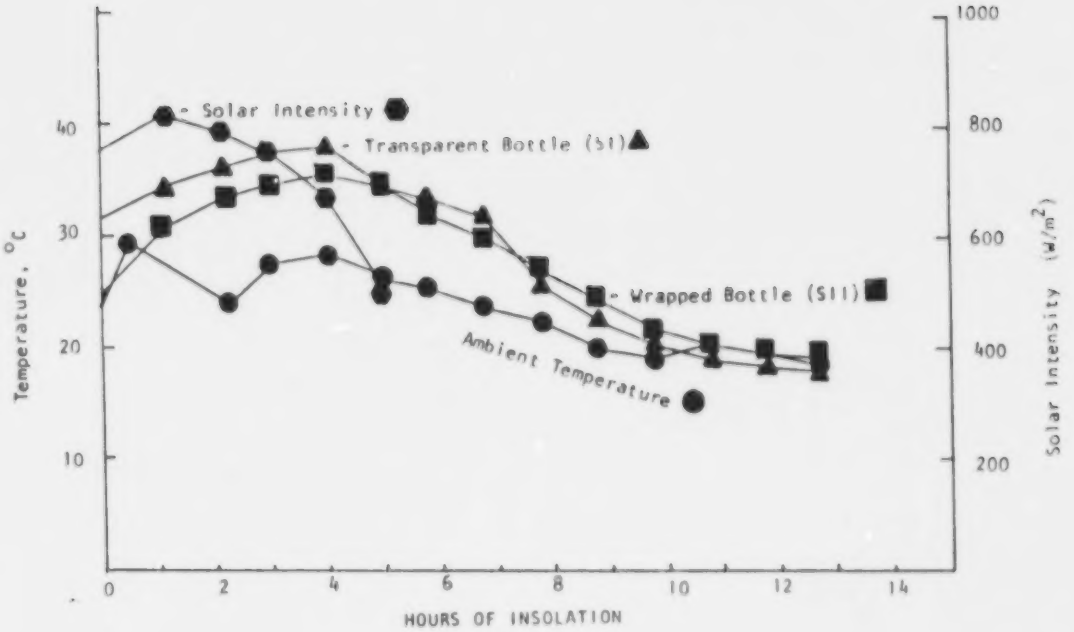

FIGURE 5. Changes in solar intensity and water temperature upon exposure of samples of St. Lawrence River water to sunshine in transparent bottles (SI) and black paper wrapped bottles (SII) to monitor bacterial survival as shown on Figure 4.

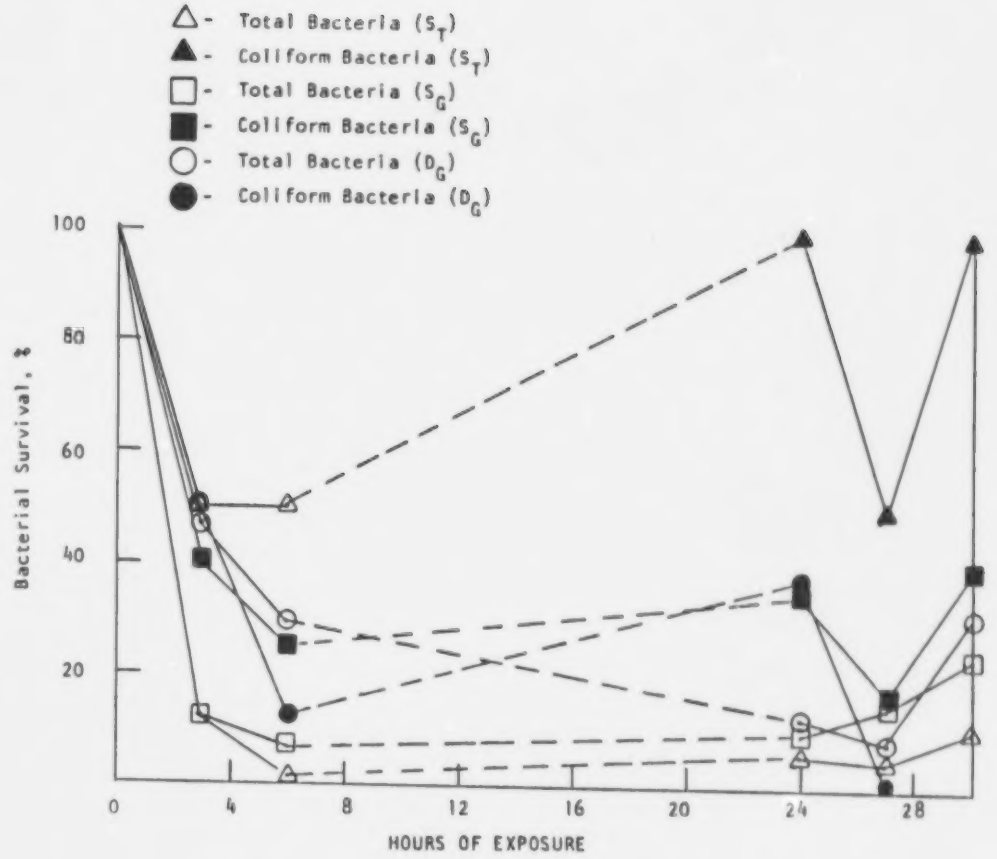

FIGURE 6. Effect of sunshine on the bacterial load of St.Lawrence River samples exposed to solar radiation in transparent bottles (S_T) and green bottles (S_G) compared with the green bottles (D_G) kept in the dark.

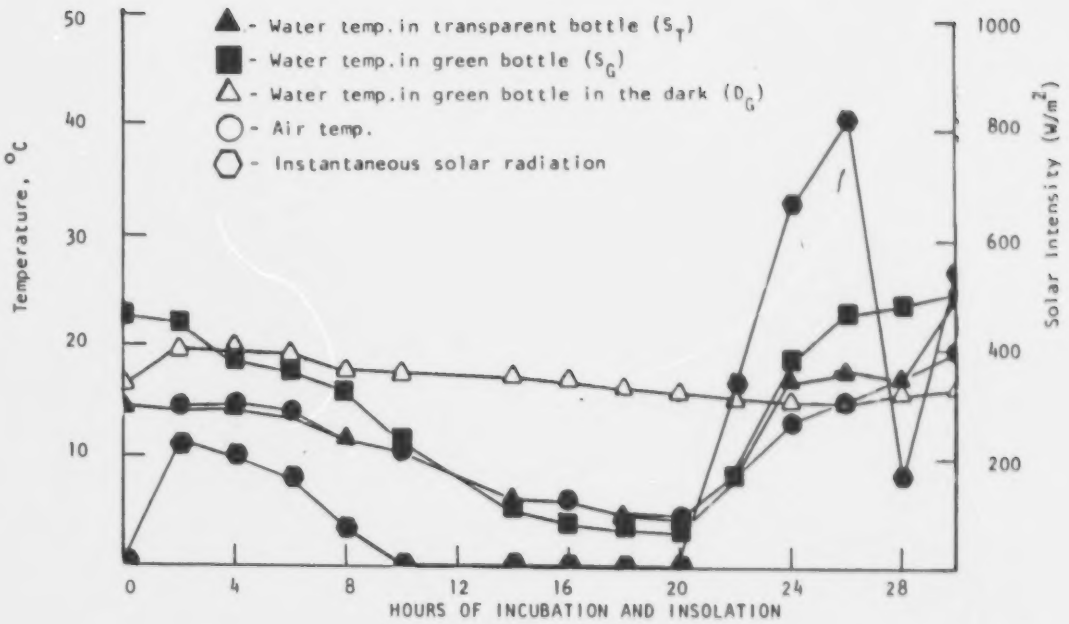

FIGURE 7. Change in solar radiation and water temperature during exposure of samples of St. Lawrence River water to sunlight in transparent bottles (S_T), green bottles (S_G) and green bottles (D_G) kept in darkness, to assess bacterial survival (See Fig.6).

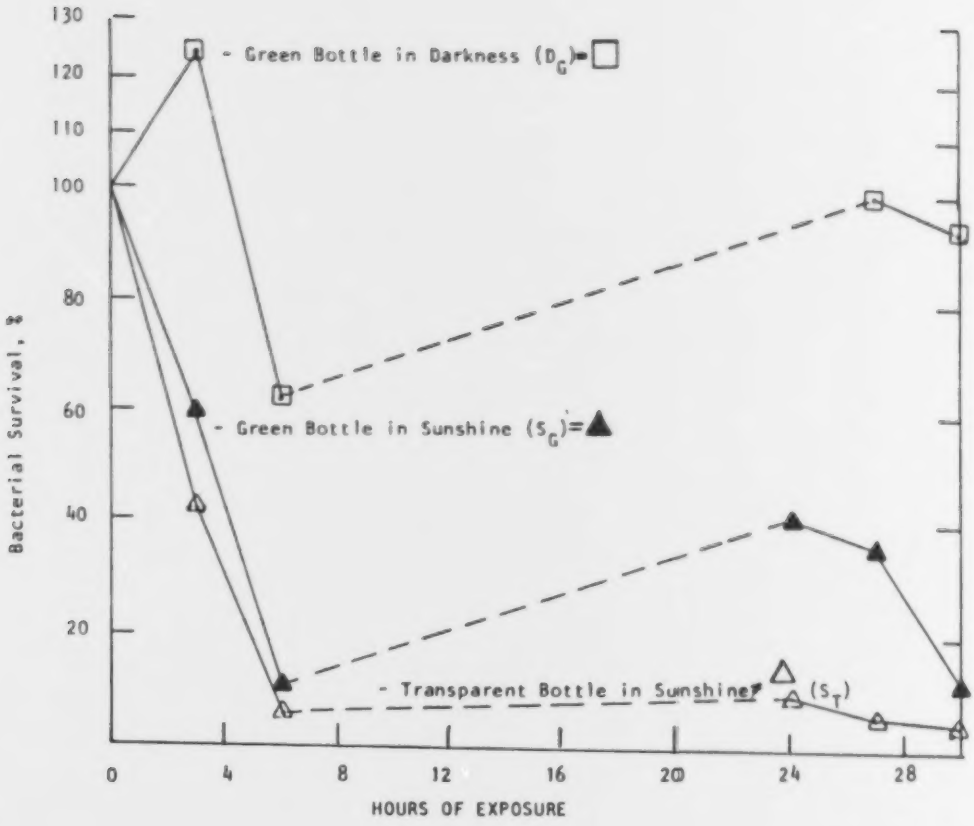

FIGURE 8. Influence of solar radiation on Shigella flexneri in St. Lawrence River water samples exposed to sunlight in transparent (S_T) and green (S_G) bottles.

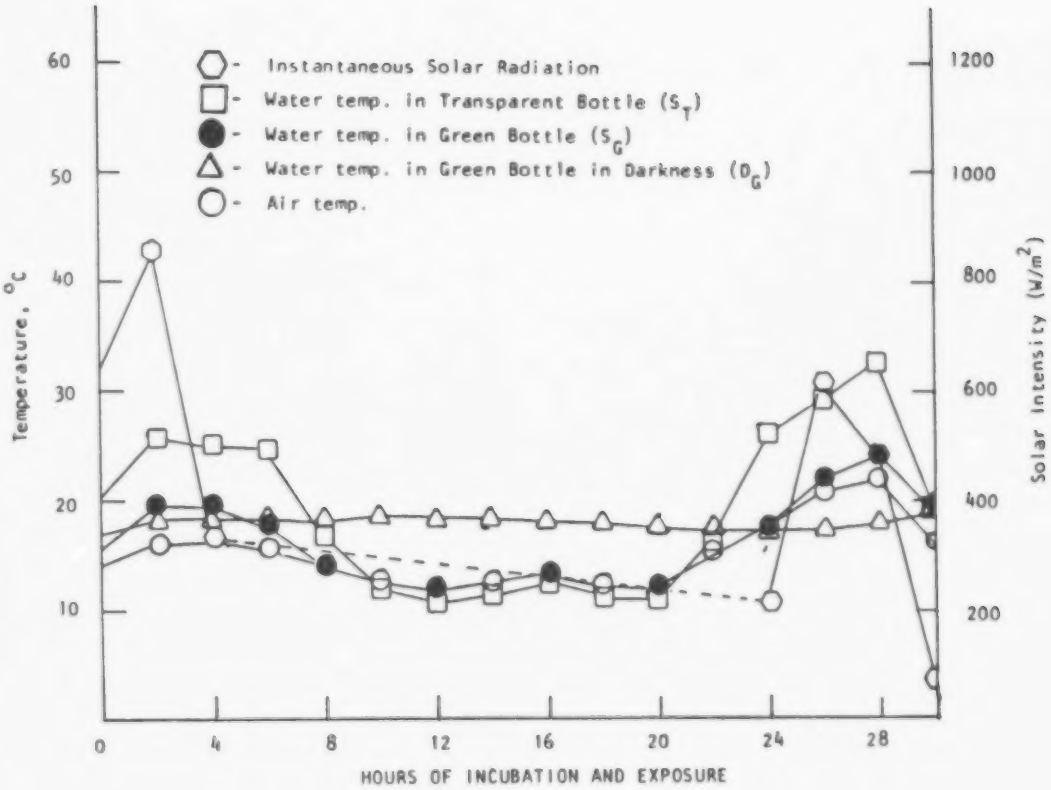

FIGURE 9. Changes in solar radiation and water temperature during exposure of S. flexneri to sunlight in transparent and green bottles (See Figure 8).

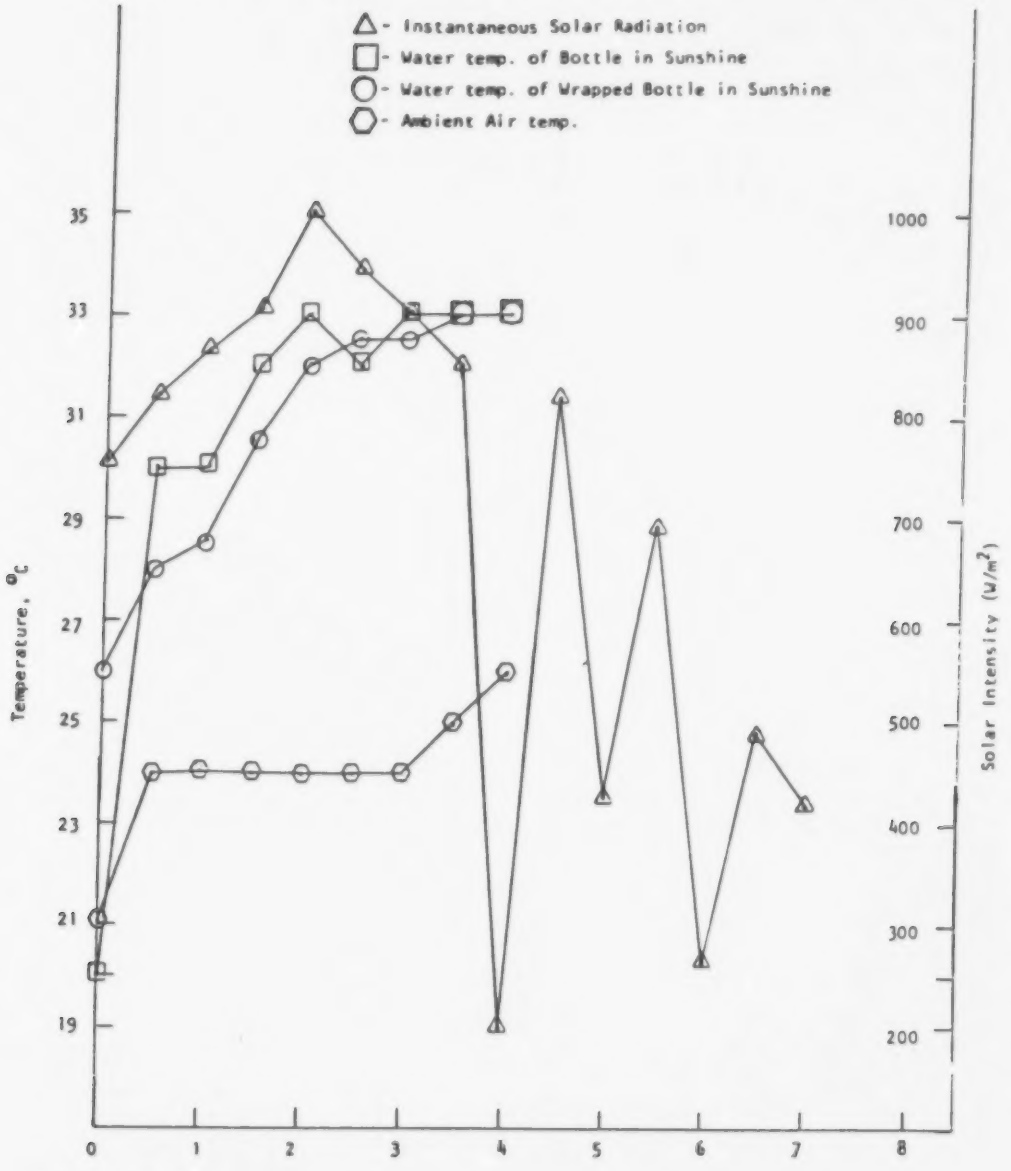

FIGURE 10. Changes in solar intensity and water temperature during exposure of G. muris cysts to sunlight in transparent and wrapped bottles (see Table 7).

TABLE A.1 GROUP OF MICROORGANISMS INVOLVED IN EXCRETED INFECTIONS
(Feachem et al., 1980)

Biological Group and Organism	Disease a/	Reservoir b/
VIRUSES		
Cocksackievirus	Various	Man
Echovirus	Various	Man
Hepatitus A virus	Infectious Heptatitis	Man
Poliovirus	Poliomyelitis	Man
Rotavirus	Gastroenteritis in children	?
BACTERIA		
Campylobacter spp.	Diarrhea in children	Animals and man
Pathogenic Escherichia coli	Gastroenteritis	Man
Salmonella typhi	Typhoid fever	Man
S.paratiphi	Paratyphoid fever	Man
Other salmonellae	Food poisoning	Man and animals
Shigella spp.	Bacillary dysentery	Man
Vibrio cholerae	Cholera	Man
Other vibrios	Diarrhea	Man
Yersinia spp.	Yersiniosis	Animals and man
PROTOZOA		
Balantidium coli	Mild diarrhea	Man and animals
Entamoeba histolytica	Amoebic dysentery and liver abscess	Man
Giardia lamblia	Diarrhea and malabsorption	Man

? Uncertain

a/ With all diseases listed, a symptomless human carrier state exists.

b/ For helminthis, the transmission process is given.

TABLE A.2 GROUP OF MICROORGANISMS INVOLVED IN EXCRETED INFECTIONS
(Feachem et al., 1980)

Biological Group and Organism	Disease a/	Reservoir b/
HELMINTHS		
Ancylostoma duodenale	Hookworm infection	Man-soil-man
Ascaris lumbricoides	Ascariasis	Man-soil-man
Clonorchis sinensis	Clonorchiasis	Animal or man-snail-fish-man
Diphyllobothrium latum	Diphyllobothriasis	Animal or man-copepodfish-man
Enterobius vermicularis	Enterobiasis	Man-man
Fasciola hepatica	Fascioliasis	Sheep-snail-aquatic vegetation-man
Fasciolopsis buski	Fasciolopsiasis	Pig or man-snail-aquatic-vegetation-man
Gastrodiscoides hominis	Gastrodiscoidiasis	Pig-snail-aquatic-vegetation-man
Heterophyes spp.	Heterophyiasis	Dog or cat-snail-fish-man
Hymenolepis spp.	Hymenolepiasis	Man or rodent-man
Metagonimus yokogawai	Metagonimiasis	Dog or cat-snail-fish-man
Necator americanus	Hookworm infection	Man-soil-man
Opisthorchis felineus	Opisthorchiasis	Animal-snail-fish-man
O. viverrini	Opisthorchiasis	Animal-snail-fish-man
Paragonimus westermani	Paragonimiasis	Animal or man-snail-crayfish-man
Schistosoma haematobium	Schistosomiasis	Man-snail-man
S. mansoni	Schistosomiasis	Man-snail-man
S. japonicum	Schistosomiasis	Animal or man-snail-man
Strongyloides stercoralis	Strongyloidiasis	Man or dog(?)-man
Taenia saginata	Taeniasis	Man-cow-man
T. solium	Taeniasis	Man-pig-man or man-man
Trichuris trichiura	Trichuriasis	Man-soil-man

? Uncertain

a/ With all diseases listed, a symptomless human carrier state exists.

b/ For helminthis, the transmission process is given.

SOLAR WATER PURIFICATION

Annotated Bibliography, Directory, and Glossary

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PREFACE

For the purposes of this report, Solar Water Purification is defined as the technique developed by Aftim Acra et al. (Beirut, Lebanon), in which polluted water is exposed to sunlight in order to inactivate its bacterial load.

The general objectives of this annotated bibliography and directory on Solar Water Purification are:

a) To serve as a quick and **updated reference guide** for the publications dealing with this sterilization technique. Reports related to this field, such as the biological effects of ultraviolet light, the physics of UV radiation, the measurement techniques for solar irradiation, the aquatic photo-chemistry and photo-biology, etc., are mentioned only if they directly relate to the subject.

b) To make available a more **detailed summary** of the publications of the research projects sponsored by the United Nations University (Tokyo, Japan), the International Development Research Center (Ottawa, Canada) and the Brace Research Institute and INRESA Secretariat (Ste. Anne de Bellevue, Quèbec, Canada). Other publications are briefly summarized.

c) To present a **list of names and complete addresses** of the research groups, main investigators, sponsoring agencies, and the institutions related to research and support in the field of Solar Water Purification.

d) Also listed are the names and addresses of the authors of the cited publications and the most important periodicals covering related subjects.

To facilitate the work of researchers in this field, the purposes of this report are: 1) To present useful and condensed background information related to the technique, and 2) to permit an easy and updated overview of the related publications. It is not meant as a comprehensive state-of-the-art review. The author of each publication or the Brace Research Institute can provide additional information.

The bibliographic references and the Directory are organized by theme and then listed in alphabetic order by author. At the end of this report are located the Subject and Name Indexes that can be used for finding a specific publication, name or address. Also included are a brief Solar Water Purification Glossary and an Abbreviations List.

1. ANNOTATED BIBLIOGRAPHY

This annotated bibliography places emphasis on the publications of the past few years. The following McGill University libraries were consulted (the abbreviations given in each of the summaries indicates the library where the reference is found):

- Brace Research Institute (**BRI**): see the complete address in section 2.3.1.
- Macdonald College (**MDC**): Barton Building, Macdonald College, Ste. Anne de Bellevue, Quèbec H9X 1C0.
- Physical Sciences and Engineering (**PSE**): Macdonald Stewart Building, McGill University, Montrèal, Quèbec H3A 2T6
- Botany and Genetics (**BG**): Stewart Biological Sciences Building, 1205 Doctor Penfield Avenue, McGill University, Montrèal, Quèbec H3A 2T6
- Medicine (**MD**): McIntyre Medical Sciences Building, 3655 Drummond Street, McGill University, Montrèal, Quèbec H3A 2T6
- Blacker Wood (**BW**): Redpath Library Building, McGill University, Montrèal, Quèbec H3A 2T6

The recommended publications are marked with an asterisk (*) at the beginning of their summary. The reports of the projects sponsored by UNU, BRI/INRESA and IDRC are extensively summarized. Other available and related publications are briefly summarized. Each publication has an identification number according to its section, i.e. publication number 3-14 is the fourteenth of section 1.3. (UV effects on microorganisms).

1.1. Project Publications

1-1. Acra, A. et al. (1980). Disinfection of Oral Rehydration Solutions by Sunlight. **The Lancet** 2: 1257-1258.

*** (BRI)**

Oral Rehydration Solutions (ORS) were prepared by mixing the World Health Organization (WHO) salt formula with chlorine-free tap water in the prescribed manner, and then contaminated with raw sewage. These ORS were placed into polyethylene bags (0.13 mm wall thickness and a minimum of transmittance below 230 nm) and then arranged into three groups: one exposed to direct sunlight, another kept under room conditions and the third was kept in complete darkness. More than 50 experiments were conducted, with the final results summarized below:

	Initial count	Sunlight 2 hrs	Darkness 2 hrs	Room 2 hrs
Coliforms/ml	71	0	15	14
Total bacteria/ml	1550	155	2240	1625
S. faecalis/ml	75	0	27	26

The conclusions are that after one hour of exposure, all the coliforms die independently of the small rise in the solution temperature (less than 5°C). The pH

and the concentration of sodium bicarbonate did not change and there was no regrowth after 24 hours. The germicidal action seems to be exerted by ultraviolet radiation with wavelengths between 300 and 400 nm.

1-2. Acra, A. et al. (1984). **Solar Disinfection of Drinking Water and Oral Rehydration Solutions. Guidelines for Household Application in Developing Countries**, American University of Beirut UNICEF, Beirut. 56 pp.

*** (BRI)**

Introduction

"Revolution for Children" is the name of UNICEF's campaign that supports the Oral Rehydration Therapy (ORT) for reducing the devastating effects of diarrhoea, malnutrition and promoting low-cost techniques for saving as many as 25000 children per day from the top morbidity and mortality causes: diarrhoeal disease and upper respiratory tract infection.

Oral Rehydration Therapy (ORT)

UNICEF's four principal measures for saving about 7 million children per year are: Growth monitoring, Oral rehydration therapy, Breast-feeding and Immunization GOBI, supplemented by Family spacing, Food supplements and Female education FFF.

A basic requirement for the ORT is a safe drinking water supply. Water is the main source of more than 25 microorganisms and parasites that cause diarrhoea, most of which are transmitted in a faecal-oral route. These are some of the reasons for the establishment of the International Water and Sanitation Decade 1981-1990, that aims at providing clean and safe drinking water and sanitation to all human beings.

Diarrhoea controlling strategies include: cleanliness, hygienic food preparation and storage, clean and adequate supply of water and appropriate excreta and refuse disposal.

Diarrhoea causes loss of water, electrolytes and impairs intestinal absorption. These effects can be controlled with Oral Rehydration Solutions (ORS) made of anhydrous glucose (20.0 g), sodium chloride (3.5 g), sodium bicarbonate (2.5 g) and potassium chloride (1.5 g) diluted in one liter of cold water (UNICEF/WHO formula). Similar rehydration solutions can be prepared at home with sugar and salt or bought in different forms at pharmacies and stores.

Problems arise during the storage of the solutions or the dehydrated salts because of humidity, internal reactions, deterioration of the package and the salts, effects of temperature and light, etc. Difficulties are also found during the preparation of the solutions due to the measurement of volumes, quality and availability of ingredients, accuracy in preparation and lack of safe water. A special problem in developing areas is the disinfection of the water that is going to be used, because of the lack of resources for boiling, the time it takes and the health hazards it poses.

Solar Energy

Fundamentals are given on solar constant, spectral bands, scattering, transmission,

absorption, reflection and world distribution of solar energy. The most favourable belt for receiving and using solar energy is located between 15 and 35 degrees of latitude north and south, in a semi-arid environment, with more than 90% of direct solar irradiation and more than 3000 hours of sun per year.

For disinfection purposes, the most effective solar spectral band is the ultraviolet, especially the near UV (300-400 nm) with an optimum at 357 nm. The angle of incidence is important and an inclined receiver, facing south in the northern hemisphere or vice versa, will receive the most. Even though scattered radiation is still effective, direct irradiation is the best. Clear glass, polystyrene, polyethylene and metacrylate transmit UV-radiation above 300 nm fairly well. In clear water the decrease of solar energy (300-500 nm) is less than 5% per meter.

Solar Disinfection

Several different disinfection techniques are discussed (boiling, sodium hypochlorite, tetraglycine hydroperiodide, etc.) and the experiments on solar water purification initiated in 1979 are described. The results clearly show that with a 95 minute exposure to the sun (always between 09:00 hours and 14:00 hours in Beirut) 99.9% of the faecal coliforms of a contaminated water sample were killed (300 minutes were required for inactivating 99.9% of the total bacteria).

Other tested microorganisms and their inactivation times were:

P. aeroginosa	15 min.
S. flexneri	30 min.
S. typhi	60 min.
S. enteriditis	60 min.
E. coli	75 min.
S. paratyphi	90 min.
Coliforms	80 min.
Aspergillus	3 hrs.
Candida	3 hrs.
Geotrichum	3 hrs.
Penicillium	8 hrs.

The germicidal effect is altered by the turbidity of the solution, the colour of the container (the best are transparent or light blue or green), the wall thickness, the shape (best are the round or cylindrical) and the local climatic conditions.

The experiments of solar disinfection of Oral Rehydration Solutions are also described (see Acra et al. (1980) in this bibliography).

Instructions

The solar disinfection of water or ORS should be done every day or every other day and the containers should be kept closed and clean. Labels have to be removed and shadows and turbid waters have to be avoided. Special care is recommended against recontamination and a minimum exposure time of 2 hours at full noon sun is needed.

1-3. Acra, A. et al. (1987). **Solar Ultraviolet Radiation: Assessment and Application for Drinking-Water Disinfection**, Project Report to IDRC. 205 pp.

*** (BRI)**

Solar UV radiation in Beirut
Concepts on solar energy, ultraviolet radiation, and their transmission through atmosphere, glass, water and other media is extensively discussed, supplemented with physical and geographical background information.

Some of the solar conditions of Beirut (34°N) are reported as follows:

Max. intensity (June, horizontal surface):	1820 uW/cm^2/month
Max. intensity (Feb., vertical surface):	705 uW/cm^2/month
Min. intensity (Dec., horizontal surface):	408 uW/cm^2/month
Min. intensity (June, vertical surface):	275 uW/cm^2/month
Annual mean (horizontal surface):	1070 uW/cm^2
Annual mean (vertical surface):	480 uW/cm^2
Daily maximum at:	11:45 hours
Daily minimum at:	8:35, 17:00 hrs.

If the container was inclined with a 35x angle facing south, the received amount of solar energy was always greater than on a vertical or horizontal position. The relation of UV-A:UV-B at ground level was found to be about 100:1 and the months with most irradiation were those from May to September.

Flow-through system for solar disinfection of water
Different techniques of disinfection are evaluated and compared to the solar purification of water in small batches (see A. Acra et al. 1980 and 1984 in this bibliography).

Four prototypes for large scale solar water decontamination were constructed and tested. Each one had a storage reservoir connected to a constant head-tank, from which a serpentine pyrex tube conducted the water (under controlled flow) on a southward inclined (35°) metallic surface to the final distribution tank. The basic characteristics are described as follows:

	Reactor type			
Characteristics	IA	IB	IIA	IIB
Tube length (m)	13.4	12.0	10.52	10.52
O.D. (mm)	22	25	12	12
Wall thickness (mm)	1.5	1.5	1.0	1.0
Capacity (l)	4.87	5.2	1.0	1.0
Pyrex containers (#)	-	-	2	4
Container cap. (l)	-	-	4.23	4.23
Total cont. cap. (l)	-	-	9.46	17.92
Storage reservoir capacity:	150 l			

The water was contaminated with settled fresh sewage (0.2-0.7% solutions), so that a starting bacterial population of 50-5000/ml was obtained. Pure cultures were also used. The trials were performed between 9:30 hrs. and 13:30 hrs., with sampling and measurements done every 30 minutes, to get data on temperature, bacterial tests, mean flow rate (used for calculating volume and residence time) and solar UV intensity.

The inactivation of the bacteria in continuous flow follows a first order kinetic equation of the type: $N/No = [e]^{-kIt}$

where No = initial bacterial density; N = final bacterial density
N/No = survival ratio; e = 2.7182
k = inactivation rate constant (cm^2/uW-min)
I = UV-A intensity (uW/cm^2)
t = exposure time or residence time = tube capacity/flow rate

The obtained results in reactors IA and IB do not differ significantly ($p < 0.001$). The tested flows were between 4 and 37 l/hr., (residence times between 66 minutes and 8 minutes). The inactivation decreased exponentially with the increase in wavelength (75% at 320 nm and 30% at 490 nm). Only UV-A (> 300 nm) accounts for the germicidal effect.

S. faecalis was more resistant than coliforms, which were more resistant than **E. coli** (the inactivation times were, respectively: 160, 150 and 115 min). The results are carefully compared to previous reports on UV inactivation of these and other microorganisms.

The conclusions are that all the tested reactors perform very well, but more experimentation is needed (especially on the IIA and IIB prototypes) in order to increase the productivity and diminish the costs. **S. faecalis** is recommended as the indicator bacteria and an additional 10 to 20% fluence is recommended for safety purposes, in addition to the minimum fluence of 17.8 W-hr./m^2 needed to kill 99% of this enteropathogenic bacteria.

Flow-through system for halosol (halogen/solar energy) disinfection of water
Conventional water disinfection methods are discussed, focusing on their advantages and disadvantages. The halosol system is described and the results of batch and flow-through experiments are reported. In the batch trials, 5 liter containers were used for studying the removal of excess chlorine and iodine from treated water exposed to sun, with a 99% reduction obtained in 72 minutes and 215 minutes respectively. Effects of shape, temperature, pH and material of the container are discussed.

For the flow-through system the IA and IB prototypes were used. The experimental procedure followed was similar to the preceding solar water disinfection, and a similar first order kinetics equation is proposed for the removal of excess halogens. The results reported show a photo-dechlorination of 99% with a fluence of 19.3 W-hr./m^2.

A discussion on the effects of temperature, pH and the physical and chemical properties of water on the photodehalogenation process follows. The conclusions and recommendations are: the halogens and possibly their haloforms are sensitive to UV-A (310-400 nm); their photodecomposition occurs in glass with a diameter of up to 20 cm and is a function of exposure time and intensity. The halosol process is functional with a wide range of applications, but needs some adjustments to local conditions.

1-4. Arafa, S. (1987). **Evaluation of Solar Disinfection of Nile and Underground Water for Drinking Purposes in Egypt**, (Final Report to UNU), American University of Cairo, Cairo, 49 pp.

*** (BRI)**

Introduction
The epidemiological data related to water-based diseases is discussed in relation to the International Drinking Water Supply and Sanitation Decade. The characteristics of water in order to be potable are: to be clear, non-saline, free of pathogens, without dangerous chemicals, less than 10 coliforms per 100 ml and less than 5 **E. coli** per 100 ml. The bacteriology of natural waters is extensively discussed in terms of types of water, types of pathogenic and non-pathogenic bacteria, natural purification processes, water-borne diseases and tests.

Objectives, Methodology and Experimental Work
The following objectives for this research are mentioned: to test and evaluate the experiments of Acra et al. in Egypt's conditions; to evaluate Egypt's rural water sources and to develop a rural disinfection technique.

The optical transmission, absorption and ESR characteristics of 10 different bottles available in Egypt were obtained. A field survey of the water supply in the Basaisa village (100 km NE of Cairo) was conducted. Water samples from the different sources in the village, and clinically contaminated water samples were exposed to sunlight for up to 5 hours and bacteriological counts of total bacteria, coliforms, **E. coli, Staphylococcus, Pseudomonas** and **Klebsiella** were made. The effect of the container volume, shape and material under natural and artificial lightning were investigated. Temperature and radiation measurements were taken.

Results
The results indicate that the most frequent impurity found in the tested glass are iron, copper, cobalt, chromium and manganese salts. The water sources in Basaisa showed bacterial counts from 2.1×10^4 /ml to 1000.0×10^4/ml and the deeper the well, the less contaminated it was.

The germicidal effect of sun caused the total inactivation of **E. coli** after 3 hours (as compared to 5 hours for room conditions). The total bacteria kept in darkness increased their number during the first 3 hours (as opposed to a survival of less than 5% after the same period exposed to sun). **S. aureus**, **P. aeroginosa** and **K. pneumoniae** were completely inactivated after one to two hours of exposure.

In order of effectiveness, transparent containers were the best, followed by turquoise glass, deep green glass, bluish plastic and light brown glass. The temperature of the sample did not rise as much in the colourless container as it did in other containers. The temperature of the sample was increased most by red artificial light, that also exerted the least germicidal effect.

Discussion and Conclusions
The transmission of solar energy depends on the colour of the container, the thickness of its wall, the refractive index and the studied wavelength. Near UV is responsible for the inactivation of bacteria in water exposed to sun. The small temperature rise in the sample, caused by sunlight, did not affect the germicidal action. Diffuse daylight

shows slower bactericidal action. Water disinfected by this technique can be stored for more than a week without regrowth.

1-5. Ayoub, J. (1986). **Use of Solar Radiation for Water Disinfection**, (Fact sheet on Odeyemi's publications). Brace Research Institute, F.36; 14 pp.

*** (BRI)**

The importance of water for all life processes, its scarcity in some developing countries and its relationship to diseases are discussed. The definition, the objectives and the aim of the solar water disinfection technique are explained. Acra's studies and the preliminary results of INRESA's researchers are summarized.

Suggestions are made for future investigative guidelines, placing emphasis on: the identification of prevalent local pathogens; the effects of physical characteristics of the container; the interference caused by water impurities and sources; the effects of depth, temperature, pH and volume of the exposed water; the climatic conditions; the results of socio-economic surveys and the necessity of avoiding recontamination. Recommendations for the standardization of this water purification technique are made.

Finally a publications list is given together with a brief description of the new Swab and Count technique used by Odeyemi for a part of his research (see Odeyemi 1986a, 1986b, 1987 in this bibliography).

1-6. Baldi, G. (1986). **Desinfeccion de agua potable con radiacion solar en el Peru**, Informe Mini-Projecto UNU, Piura, Peru. 43 pp.

*** (BRI)**

Introduction
The relationships between poverty, diseases and contaminated water sources are highlighted. Acra's findings and the research projects sponsored by the United Nations University (Tokyo, Japan) are described.

Potable water in the rural areas of northern Peru
Taking as an example the Piura region in northern Peru (population 1.300.000, latitude 4-6°S and longitude 81-79°W), the situation of the water supply and sanitation of many rural areas of Peru is explained. An estimated 62% of the houses have no public water and sanitation services; 50% of the inhabitants are 15 years old or less and the infant mortality rate is 6.7%. In this large semi-desert area, only two valleys are suitable for cultivation.

The public water supply is extremely inefficient (about 30,000 people are served, of a total of 500,000) and quickly deteriorating. The usual water sources are deep wells, small rivers, open ponds, draining and irrigation canals, together with cistern-based transport system. Bacteriological analysis shows a high pollution (up to 350 coliforms/ml for public supply and up to 1600+/ml for natural sources).

Water-related diseases are the second cause of mortality and morbidity among children, especially gastroenteritis, different diarrhoeas, typhoid fever, dysenteries, etc.

Solar water disinfection possibilities
The following three aspects were analyzed:

1) Solar energy: Peru and Piura have enough solar energy for this technology (minimums of 4.8 and 4.3 kW-hr./m^2-day, respectively). There is an average of only two days per year with less than 1.5 kW-hr./m^2-day intensity in Piura (min. dose for killing **Salmonella** spp.).
2) Local pathogenic microorganisms: The principal pathogenic agents are: **E. coli, Salmonella typhosa, S. paratyphi, Shigella disenteriae** and **Enterovirus**.
3) Local customs and habits: The containers used for transporting water are usually 10-30 l metal or plastic boxes. Ceramic containers with a capacity of 50-100 l are used for storing it. Transparent bottles are not very frequent (only some 2 l soft drink ones). Because of this situation, open, metallic, non-transparent containers had to be tested. A theoretical analysis showed that these should exert a double germicidal effect upon the bacteria, if the walls were reflective and they were tested near to the Equator.

First solar water purification experiments and conclusions
Five transparent and one green bottles are used for testing the effect of the sun on the bacteria in three sets: full sunlight, room conditions and darkness. Four bottles and two metallic boxes (one new, one old) were used for testing the effect of the container. The water from different sources was contaminated on purpose.

The results show that the coliforms are completely inactivated in one hour, but the total bacteria were only reduced by 50% after 2.5 hours of full sun. Under room conditions the total bacteria were reduced by 50% and the coliforms by 65% after 2.5 hours. In darkness both were reduced by 25 to 30% after 2.5 hours. 45 minutes were needed for inactivating all the coliforms in the old box, but 90 minutes were necessary for the new one.

The water temperature in the sun-exposed bottles increased from 24 to 41°C, and in the boxes to 36 degrees. In room conditions and darkness the temperature increased to 28°C. The irradiation received ranged from 300 to 1000 kW/m^2.

The conclusions are that **E. coli** and the coliforms are easily inactivated in about two hours, independent of the type of container, and that the change in water temperature does not play a major role in the germicidal effect of the sun, at least below 43°C. It was found that when water from an open, exposed supply was tested, the total bacteria in it showed more resistance to be inactivated.

It is necessary to further research the effect of a previous exposure of the water to sun in order to detect resistance. The effects of pH and temperature have to be investigated and different containers must be tested.

1-7. Cotis, M.C. (1986). **Application of Optical and Electron Spin Resonance Measurements to the Solar Disinfection of Drinking Water.** M.Sc. Thesis, The American University in Cairo, Cairo, 146 pp.

*** (BRI)**

The problem of safe drinking water for developing areas and the aim of this work are explained, based on the results of A. Acra et al. in Beirut (Lebanon) and G. Baldi in

Piura (Peru). Background information on solar radiation, spectrophotometry and optical absorption in solids and liquids, electron spin resonance (ESR) of amorphous solids and the bacteriology of natural waters is extensively provided. The field and material surveys, measurements and bacteriological tests performed are described in detail. The results in terms of the optical and ESR measurements made on the materials of the researched containers, the bacteriological tests and counts, and the field surveys are presented, discussed and concluded upon. For a partial summary of this publication, as far as it is related to solar water disinfection, refer to S. A. Arafa (1987) in this bibliography.

1-8. Dube, F. (1988). **Personal Communication** to J. Hahn. Brace Research Institute, Ste. Anne de Bellevue, 2 pp.

*** (BRI)**

A research project was initiated in August 1987 at the Brace Field Station (Ste. Anne de Bellevue, Québec, Canada) and finished on a farm near Hawkesbury (Ontario, Canada) to establish the effect of the water temperature, the inclination of the container and the use of reflectors on the Solar Water Purification technique.

The water samples were obtained from the St. Lawrence river at Ste. Anne de Bellevue and from the municipal sewage treatment plants of Vaudreuil (Quèbec) and Hawkesbury (Ontario). The tested containers were either one liter glass mason jars or one liter plastic bags. A specially designed incubator was constructed but not tested for evaluating the effect of different water temperatures.

The unpublished results show that the Swab and Count technique (Double Integral Sanitation Ltd, Mississauga, Ontario, Canada) was useful only for estimating the bacterial population of highly contaminated water. It was also found that the use of an aluminum reflector placed behind the container increased significantly the killing rate and the water temperature. A 94.4% reduction in total coliforms was achieved after 3 hours of exposure without reflectors, as opposed to 99.8% for the same conditions with reflectors.

1-9. INRESA Secretariat (1985). **Simple Solar Water Purification System Testing and Evaluation**. Proposal sent to U.N. University, Tokyo, n.pp.

*** (BRI)**

This is the original research proposal sent by the Secretariat of the Integrated Rural Energy Association (INRESA) at Brace Research Institute (Ste. Anne de Bellevue, Canada) to the United Nations University (Tokyo, Japan).

It contains all the background information for the proposed investigation network (justification, objectives, methodology, work plan, budget, etc.) and the individual proposals submitted by each of the research teams.

1-10. INRESA Secretariat (1987). **Simple Solar Water Purification System Testing and Evaluation Interim Report**. Brace Research Institute, 11 pp.

*** (BRI)**

This is an internal report with a summary of the 1986 activities of the United Nations University (UNU, Tokyo, Japan) research contract with the Integrated Rural Energy Association Secretariat (INRESA) at Brace Research Institute (Ste. Anne de Bellevue, Canada).

A brief background on water-related diseases and their morbi-mortality is given, together with a description of A. Acra's findings and methodology.

Early results and an outline of the future work of each of the following research teams are given:

S. Arafa and M. Cotis (Egypt)
G. Baldi and M. Fiestas-Chunga (Peru)
O. Odeyemi (Nigeria and Canada)
B. Sepalage et al. (Sri Lanka)
J. Zapp et al. (Colombia)

A short comment on the difficulties with the instrumentation equipment and on the circulating INRESA-Newsletters is made. Finally, a publications list is attached.

1-11. Koottatep, S. (1988). **Natural Disinfection of Rural Water Supply by Solar Irradiation.** Final project report to IDRC. Chiang Mai University, Chiang Mai, Thailand. 194 pp.

*** (BRI)**

A socioeconomic study of three villages in rural Thailand (Ban Huai Sai, Ban Plaeng Ha and Ban Huai Tom) was performed. Analyzed parameters were: housing characteristics, sanitation conditions, eating habits, health, personal hygiene, income, education, household size, communication, etc. An assesment of the quality of their water supply and of the feasibility of using solar irradiation as disinfection technique was also carried out.

It is reported that most of the water sources had bacterial loads above the drinking water standards. Improvement of the wells did not improve the water quality, therefore it is concluded that a disinfection technique is necessary.

A flow-through system for water disinfection using solar energy was designed, built and tested. The UV-disinfection model did not show consistent bacterial killing, whereas the rise-in-temperature model could reduce successfully the faecal coliform load of the tested waters. With a copper solar plate, a 100% reduction of faecal coliforms is reported with a retention time of 15 minutes and a water temperature of 60°C. The models were tested always from 11:00 to 15:00 hours on clear, sunny days. Other tested models included a glass and a steel tube solar plates, in which a longer retention time (20 to 40 minutes) was necessary for the same inactivation rate.

It is concluded that the copper solar plate and the glass tube solar plate could be improved and applied for use in real conditions. The treated water could be stored afterwards in traditional clay jars without changing its quality.

1-12. Odeyemi, O. (1986a). **Use of Solar Radiation for Water Disinfection**. Report of INRESA Secretariat, Ste. Anne de Bellevue, Canada, 33 pp.

*** (BRI)**

Introduction
At least 50% of the people in developing areas of the world have no access to safe drinking water supplies nor adequate sanitation facilities. This originates a vicious cycle of water-borne diseases (responsible for 80% of the sicknesses) and deaths (about 25 million people, 60% of which are children). 39 pathogenic water-related organisms are discussed.

A review of A. Acra's research is made, complemented with a summary of the different projects undertaken by BRI, UNU and IDRC in various parts of the world.

Materials and Methods
The Swab and Count technique (Double Integral Sanitation Ltd., Mississauga, Ontario) is evaluated against the traditional direct plate count technique. This relatively new technique consists of a swab in a plastic tube filled with buffer and a dip slide with two types of media. The water samples were taken from the St. Lawrence river at Ste. Anne de Bellevue, Quèbec, and from the sewage treatment plant at Beaconsfield, Quèbec. 10% solutions were prepared for the experimental work.

The samples were kept in sunlight, darkness, vertical and horizontal position of the container and the effects on pure cultures of **Salmonella typhi, Staphylococcus aureus, Shigella flexneri** and **Giardia muris** cysts were investigated.

Results and Discussion
The Swab and Count technique is fairly accurate if the cell concentration is greater than 500/ml and water vapour inside the test tubes is avoided.

The bacteria in the diluted sewage were reduced to 10-16% of the initial count after 4 hours of exposition. In opposition, after 24 hours of darkness the number increased by 100 300%. Plastic containers seem to be more effective than glass containers for the inactivation, but no total kill was achieved.

No significant difference was noted between horizontal and vertical positions. In both cases the coliforms disappeared after 3 hours of exposure and the total bacteria were reduced by 99.9% after 6 hours.

S. typhi and **S. aureus** were completely killed in 3 hours, without regrowth, but survived more than 24 hours if kept in darkness. Clearly the sunlight and not the change in temperature was the cause of their inactivation.

Some of the results of the St. Lawrence river water samples are summarized in the following table:

	Direct sun 3 hrs.	Wrapped in sun 3 hrs.	Darkness 3 hrs.
Total bacteria reduced to:	8%	14%	60%
Coliforms reduced to:	0.1%	50%	30%

Transparent or green containers do not seem to affect the results, as is shown with the reduction to 43 and 60% of the initial count of **S. flexneri** in transparent and green containers, respectively, after 3 hours of exposition. Local climatic conditions posed some difficulties.

All the **G. muris** cysts seem to be killed by the sun, but problems with the control group of mice arose during the experimentation.

Summary and Conclusions
The sun exerted full germicidal effect in 3 hours of a sunny, clear summer day at Ste. Anne de Bellevue (45°N), Canada.

Coliforms and individual, pure cultures were more senstive than total bacteria and even more if diluted in distilled water.

The sewage solutions were never completely disinfected and the best day time for this technique was from 10:00 to 14:00 hrs.

No regrowth occurred if the containers were properly disinfected and stored and the position of the container (vertical or horizontal) did not affect the results.

It was found that the solar radiation was the cause of bacterial killing, not the rise in temperature and that **Giardia muris** cysts seemed to be sensitive.

The Swab and Count technique was adequate for estimating coliforms, but is less so for total bacteria counts.

1-13. Odeyemi, O. (1986b). **Guidelines for the Study of Solar Disinfection of Drinking Waters in Developing Areas of the World**. Publ.# U/86/24, INRESA Secretariat, Ste Anne de Bellevue, Canada, 16 pp.

• (BRI)

The relationships between the rural poor, the access to a safe water supply and water-borne diseases are carefully explained. Infantile morbi-mortality as related to the International Water Decade and to A. Acra et al's research is also discussed.

Examples are used for explaining the similarities and differences between water-borne, water-related, water-based, water-related insect-mediated and aquatic food-related diseases.

The methodology to be followed for research of solar disinfection of drinking water is discussed, based on Acra et al's publications and a brief verification of his experiments is described.

Some of the suggestions proposed for further research are:

1) Local and endemic water-related diseases have to be investigated in relation to this technique, taking special care in studying the effect on spores, cysts, eggs and similar vegetative forms of endemic pathogens.
2) The types of containers and water sources, their characteristics and influence on the process must be studied. Much more climatic data is necessary, especially for most of the areas where this technique could be useful.
3) Field tests have to be carried out and data must be gathered on socio-economic aspects (water use, traditional water treatment, habits, superstitions, costs, etc.). The prevention of recontamination and the standardization of the procedure for each locality has to be established. The mechanisms of solar destruction of pathogens have to be cleared.

Finally an addendum contains the list of equipment, chemicals, culture media and other materials needed for carrying out experimentation in solar water purification.

1-14. Odeyemi, O.(1986c). Solar Disinfection of Drinking Water and Oral Rehydration Therapy (ORT). **INRESA Newsletter**, # 13.

*** (BRI)**

Based on a local Canadian newspaper article on the death of Peruvian children after ingesting U.S. supplied Oral Rehydration Solutions (ORS), a comment relates the possible causes of the tragedy to bacterial contamination of ORS and drinking water, and the urgency of developing and applying simple disinfection techniques like Solar Water Purification in developing areas of the world is highlighted.

1-15. Odeyemi, O. (1986d). A Brief Summary of a Report Entitled "Guidelines for the Study of Solar Disinfection of Drinking Waters in Developing Areas of the World". **INRESA Newsletter** # 12: pg. 18.

*** (BRI)**

An executive summary is made of the previous publications by the same author. See Odeyemi (1986b) in this bibliography for details.

1-16. Odeyemi, O. (1987). **An Assessment of Solar Disinfection of Drinking Water in Nigeria**. Final Report for UNU, (Tokyo), 34 pp.

*** (BRI)**

Introduction and Objectives

The health effects of the faecally contaminated water sources and the lack of adequate sanitation for at least 50 million people in Nigeria is discussed in terms of morbidity, mortality and the most important diseases, with emphasis placed on their

relevance for the children population.

The objectives of this research are to verify Acra et al's findings and to relate them to the local conditions, complemented with an epidemiological study on water-borne diseases and microbial and parasitic agents frequently found in Nigeria.

Methodology and Results
Epidemiological data were gathered from different sources (hospitals, universities, official health institutions, etc). Samples of contaminated rivers, ponds and wells were obtained and sterilized water was contaminated on purpose with pure bacteriological cultures. All were tested under the local conditions, assessing the effect of different climatic events. The prevalent water-borne diseases and their respective pathogens were: bacillary dysentery (**Shigella spp.**), amoebic dysentery (**Entamoeba hystolitica**), cholera (**Vibrio cholerae**) and typhoid fever (**Salmonella typhosa**).

The mean solar intensity ranged from 691 W/m^2 (10:00 hours) to 841 W/m^2 (12:00 hours), the maximum was 886 W/m^2 at noon in mid-June, and the minimum was 14 W/m^2 (18:00 hours) in early May and early June; the temperature of the solutions changed from 30°C (10:00 hours) to 40°C (12:00 hours).

The summarized results are: a 99% kill of the total bacteria was achieved in 4 hours (99.9% for coliforms). In order to get a 100% inactivation of **S. aureus**, more than 3 hours of exposure were needed, if the solution was made in distilled water. If sterilized water was used, more than 24 hours were needed. **V. cholerae** disappeared after 4 hours of strong insolation.

Clouds and heavy rain exert the same influence as darkness on the bacterial population. The disinfection was found to be faster in transparent than in green containers.

Discussion, Conclusions and Recommendations
No total kill of the total heterotrophic bacteria was achieved, but the coliforms were easily inactivated after 5 hours of exposure. Highly contaminated or turbid water can not be disinfected. **V. cholerae** requires at least 600 W/m^2 during 4 hours to be completely killed and **S. aureus** does not disappear if the water is not distilled. The best time of the day is from 10:00 to 16:00 for solar purification and the recommended time and intensity for obtaining safe water are 600 W/m^2 during at least 5 hours, but rainy and cloudy conditions interfere strongly.

The efficacy and social acceptability of this technique has to be investigated. More research is needed for establishing the effects of the technique upon other water-related pathogens and the inactivation mechanisms have to be cleared.

1-17. Sepalage, B. P. (1988). **Study of the Technical Feasibility and Potential for Purification of Water by Solar Energy in Sri Lanka.** Preliminary report to UNU. 13 pp.

*** (BRI)**

Water from the Kelain river near Colombo was contaminated with pure bacterial

cultures. The samples were exposed to sun or artificial UV light during four hours, in glass and plastic containers.

The reported results show an irregular coliform death rate probably due to residual nutrients from the inoculum. No clear difference between glass or plastic containers is reported. The use of artificial UV light did not give consistent results. Rain was found to reduce the amount of received radiation, therefore the bacterial inactivation rate was also low.

1-18. Zapp, J. et al. (1988). **Solar Water Purification in Coffee Growers Climate.** Final Report to UNU. Bogota, 55 pp.

*** (BRI)**

The Solar Water Purification technique was tested in the city of Pereira (population 287,000), located in the central mountainous region of Colombia (latitude 4° 39' N and longitude 75° 23' W).

The climatic conditions are typical for the coffee growing areas: warm (average temperature of 23°C), humid (precipitation of 2750 mm/year and 85% average humidity), high cloudiness (low radiation) and an altitude of 1400 meters.

A high population density and the waste waters from the coffee industry have a great impact upon the water quality. It is estimated that about 29% of the population have no access to safe water nor appropriate sewage.

Seven urban sites were selected for climatological and socioeconomic analysis and 11 related water sources were tested. Three sets of experiments were performed: the first ones, called preliminary tests, aimed at the standarization of the technique and at the design and construction of a portable field incubator. During the second ones, or initial tests, the water sources were analyzed and exposed to sun. For the final or secondary tests, water from two sources on the University of Pereira campus were used.

It was found that 10 out of 11 water sources actually in use were polluted with E. coli. A trend towards the reduction of the bacterial population due to the killing effects of light was noticeable, but only a few 100% kills are reported. This seems to be explained by the low local radiation. The average reduction of the total bacteria was 64.8%. Total coliforms were reduced 73% and the faecal coliforms 93.8% for the initial set of experiments. During the final set, higher inactivation percentages were obtained. In this set the maximum reduction of total bacteria was 91.9%. For total coliforms and faecal coliforms the maximum reductions were 91.9% and 97.2% respectively.

It is concluded that the Solar Water Purification technique has a lower climatic limit. Even though the conditions (low direct radiation, warm climate and highly polluted water) were not favourable, a reduction trend in the bacterial population due to the exposure to sun is noticeable.

1.2. General Photobiology and Photochemistry

2-1. Calkins, J. et al. (1976). The Role of Solar Ultraviolet Radiation in 'Natural' Water Purification. **Photochem. and Photobiol.** 24:49-57.

*** (BRI, BG, PSE)**

A mathematical model of the growth and die-off of a population of **E. coli** in tertiary wastewater systems was developed, based on the measurements done during an 11-month period of the **E. coli** input and output to the system, the temperature, the growth rate of **E. coli** at that temperature, the biologically important UV-radiation, the UV-penetration into the lagoon, the retention time and the dose-response relation for killing **E. coli**.

The expected growth and die-off for these conditions were calculated with the model and then compared to the real **E. coli** output. The conclusion is that UV-B is the main factor responsible for the killing of the bacteria, but about 1% of them survive after one week in "natural" conditions. Finally, the UV-B importance in nature is discussed.

2-2. Jagger, J. (1985). **Solar UV Actions on Living Cells**, Praeger, New York, 202 p.

*** (BG)**

This is an updated review on solar ultraviolet photo-biology by one of the most experienced researchers in the field. The book has 12 chapters, seven of which are dedicated to the effect of UV radiation on microorganisms.

The author discusses the role of solar UV in nature and the biological effects (killing, mutation, repair, membrane damages and sublethal actions) of the near, mid and far UV regions.

Also included are reviews on applications, problems, instrumentation, units, dosimetry and experimental procedures related to solar and artificial ultraviolet radiation research.

2-3. Malaiyandi, M. et al. (1980). Removal of Organics in Water Using Hydrogen Peroxide in Presence of UV Light, **Water Res.** 14: 1131-1135.

(MDC)

The application of a 50% solution of hydrogen peroxide and of artificial ultraviolet light to contaminated water, reduced its total organic carbon content by 88 to 98%. A discussion follows on the involvement of ultraviolet light in the production of free oxygen and hydroxile radicals in water treated with hydrogen peroxide.

2-4. Senger, H. (Ed.) (1980). **The Blue Light Syndrome**, Springer Verlag, Berlin, 665 pp.

*** (BG)**

This book contains extensive reviews on different aspects of UV-photobiology, focusing on the effects of blue light in nature, especially at the microbiological, biochemical and physiological levels. Also analyzed are the involved photoreceptors and primary reactions, carotenogenesis, carbon and nitrogen metabolisms, respiration and chloroplast development.

2-5. Senger, H. (Ed.) (1984). **Blue Light Effects in Biological Systems**, Springer Verlag, Berlin, 538 p.

*** (BG)**

This is a more updated publication of themes reviewed in a previous book by the same editor (see # 24, Senger (1980) in this bibliography), that contains articles on photoreceptors, signal transduction, genetic and molecular biology responses, enzyme regulation, carbohydrate metabolism, pigment biosynthesis, development, movement, growth and several ecological aspects of blue light.

1.3. UV Effects on Micro-organisms

3-1. Abshire, R. and Dunton, H. (1981). Resistance of Selected Strains of **Pseudomonas aeroginosa** to Low-Intensity UV-Radiation, **Appl. Environ. Microbiol.** 41: 1419-1423.

(MDC)

Ten different strains of **Pseudomonas aeroginosa** in saline solutions were exposed to an artificial UV light source (100 uW/cm^2). The results show that this microorganism is very sensitive to UV radiation of this intensity, and that this light was able to penetrate 40 mm deep into the solution and through the polyethylene bottles.

Other microorganisms tested were **Micrococcus radiodurans** (the most resistant) and **Staphylococcus aureus** (the less resistant).

3-2. Acher, A. and Elgavish, A. (1980). The Effect of Photochemical Treatment of Water on Algal Growth, **Water Res.** 14: 539-543.

(MDC)

The destruction of the algae **Peridinium, Pediastrum** and **Cosmarium** in water is reported, when they were exposed for 30 to 60 minutes/day to sunlight during 2 weeks, with the addition of 0.25 to 0.75 mg/l of methylene blue or 0.8 mg/l of rose bengal.

3-3. Acher, A. and Juven, B.(1977). Destruction of Coliforms in Water and Sewage Water by Dye-Sensitized Photoxidation, **Appl. Env. Microbiol**. 33: 1019-1022.

(MDC)

Water and sewage contaminated with **E. coli** were exposed to sun (0-2.03 uE/m^2/s) for up to 2 hours, with the addition of methylene blue (0-10 mg/l) under continuous aeration. An achieved destruction of 1.3 x 10^9 coliforms/100 ml in 30 minutes is reported.

3-4. Antopol, S. and Elner, P. (1979). Susceptibility of **Legionella pneumophila** to UV Radiation, **Appl. Environ. Microbiol**. 38: 347-348.

(MDC)

Distilled water contaminated on purpose with **Legionella pneumophila** was irradiated with an artificial UV light, obtaining a 99.9% inactivation with an irradiation of 2760 uW-s/cm^2 (50% kill with 380 uW-s/cm^2). It is compared to the irradiation needed for killing 90% of **Pseudomonas aeroginosa** and **E. coli** (5500 and 2110 uW-s/cm^2 respectively).

3-6. Calkins, J. and Thordardottir, T. (1980). The Ecological Significance of Solar UV Radiation on Aquatic Organisms, **Nature** 283: 563-566.

(MDC)

The quantitative estimation of exposure time, dose and tolerance to ultraviolet radiation of aquatic organisms are discussed and the significance of solar UV radiation in nature is explained. The results show that all of the studied aquatic organisms had a similar exposure and tolerance to solar UV light.

3-7. Chamberlin, C. and Mitchell, R. (1978). A Decay Model for Enteric Bacteria in Natural Waters. In R. Mitchell (Ed.): **Water Pollution Microbiology**, Vol. 2, John Wiley & Sons, New York, 325-348.

*** (MDC, BG)**

Information on mechanisms of light-induced damage, sensitivity of coliforms and non-coliforms to light and the evaluation of laboratory work with field data are given, in order to discuss a model for the decay of faecal bacteria in water under natural conditions.

The main conclusion is that coliform decay is principally due to light-induced cell damage and that the bacterial sensitivity depends on the sensitizing agent, the presence and amount of dissolved oxygen and the biochemical and ecological protection mechanisms.

3-8. Chang, J. et al (1985). Ultraviolet Inactivation of Pathogenic and Indicator Micro-organisms, **Appl. Environ. Microbiol.** 49: 1361-1365.

*** (MDC)**

Pure cultures of different microorganisms were dissolved in distilled and buffered water and exposed to artificial UV radiation (5-10 mW-s/cm^2, 254 nm). With this irradiation, a 99.9% inactivation was achieved for **E. coli, Salmonella typhi, Shigella sonnei, Streptococcus faecalis** and **Staphylococcus aureus. Enterovirus polio** type I and simian **rotavirus** required three to four times the dose needed for **E. coli. Bacillus subtilis** spores required nine times that dose and **Acanthamoeba castellani** cysts as much as 15 times in order to be inactivated.

3-9. Eisenstark, A. et al (1986). Inactivation of Phage by Near-UV Radiation and Hydrogen Peroxide, **Photoch. Photob.** 44: 603-607.

(BG, PSE)

Seven different phages (ssRNA, dsRNA, ssDNA and dsDNA) were exposed to UV irradiation and hydrogen peroxide. It is reported that for all of them (only one exception) the peroxide enhanced the killing effect of near UV but not of far ultraviolet light.

3-10. Fujioka, R. and Narikawa, O. (1982). Effect of Sunlight on Enumeration of Indicator Bacteria under Field Conditions. **Appl. Env. Microb.** 44: 395-401.

*** (BRI, MDC)**

The effect of exposure to sunlight on the enumeration of faecal coliforms and faecal streptococci is analyzed. These two groups from raw sewage, placed undiluted in transparent containers, were resistant. If they were diluted 1:100 in sea water, 90% were inactivated after 32 minutes. If diluted in the same proportion in fresh stream water, 90% of the coliforms were killed after 38 min and 90% of the streptococci after 2 hours. Placed on membranes and exposed to sunlight, 90 to 99% of both were inactivated in less than 15 min.

The streptococci were always more resistant than the coliforms. During the first 15 to 30 minutes of exposure, only sublethal injuries occur. An increase of the solution temperature up to 45°C did not affect the photo-killing. Clear glass, clear polyethylene and polystyrene do not affect the bactericidal effect of the sun.

3-11. Fujioka, R. et al (1981). Effect of Sunlight on Survival of Indicator Bacteria in Sea Water, **Appl. Env. Microb.** 41: 690-696.

*** (MDC)**

Faecal coliforms and streptococci from raw sewage were diluted 1:1000 in seawater, phosphate-buffered water and fresh stream-water and then exposed to sun. Water temperature was 24°C.

The results show that 90% of the coliforms were inactivated after 30 to 90 minutes of exposure and 60-180 minutes were necessary for the same inactivation percentage of streptococci. The germicidal action of the sun was exerted through glass, polyethylene and 3.3 m of clear seawater.

The tested bacteria were more resistant when diluted in fresh water. Some of the germicidal effect could be attributed to the visible range of sunlight.

3-12. Gameson, A.L. and Saxon, J. (1967). Field Studies on Effect of Daylight on Mortality of Coliform Bacteria, **Water Res.** 1: 279-295.

(MDC)

A mixture of seawater and fresh sewage was kept in transparent glass bottles at different depths (down to 4 m below surface). It was found that the mortality caused by daylight is proportional to the intensity of the short wave radiation, therefore during May a 90% kill was achieved with 60 cal/cm^2 and in September the same proportion was killed with 150 cal/cm^2.

3-13. Grigsby, P. and Calkins, J. (1980). The Inactivation of a Natural Population of Coliform Bacteria by Sunlight, **Photochem. and Photobiol.** 31: 291-294.

*** (BRI, BG, PSE)**

"Natural purification" is defined as the natural process of removing pathogens from contaminated water. In order to assess the importance of light for it, 120-ml samples of polluted water were placed into UV-transparent and UV-absorbent cylinders, then located into a 50 l container filled with lagoon water and exposed to sunlight during 3 days. Different wavelengths were tested by using specific filters for each one.

The results show that coliforms grow quickly in dark, protected conditions and during the night, but less than 0.01% survive one day of full exposure to sun. Light with wavelengths above 325 nm is able to kill the tested bacteria. The main conclusion is that ultraviolet radiation is a substantial contributor to the process of natural purification.

3-14. Hader, D. (1986). Effects of Solar and Artificial UV Irradiation on Mortality and Phototaxis in the Flagellate **Euglena gracilis. Photochem. Photobiol.** 44: 651-656.

(BG, PSE)

It is reported that UV-B impairs movility, phototactic orientation and survival of **Euglena gracilis** within 2 hours of exposure. UV-A, temperature and the visible range of light were not found responsible for the mentioned effects. Glass and ozone layers decreased the observed reactions. It is supposed that UV-B affects the nucleic acids or a special UV-absorbing molecule.

3-15. Harris, G.D. (1987). UV Inactivation of Selected Bacteria and Viruses with Photo Re-activation of the Bacteria, **Water Res.** 21: 687-692.

(MDC)

Ultraviolet dose and survival response curves for **E. coli, S. faecalis**, poliovirus and reovirus were obtained. It was found that reovirus was the most resistant of the viruses, which in turn were more resistant than the bacteria. Of these, **E. coli** was the most sensitive.

3-16. Huber, A. and Schrott, E. (1980). Photokilling and Protective Mechanisms in **Fusarium aquaeductum**. In H. Senger (Ed.) **The Blue Light Syndrome**. Springer Verlag, Berlin: 300-308.

(BRI, BG)

Blue and near UV lights, under aerobic conditions, induce carotenogenesis in some non-photosynthetic bacteria and fungi. At the same time, they exert a photo-killing effect. This carotenogenesis induced by light seems to be a protective mechanism against damages at the mitochondrial level.

The effective wavelengths and fluences studied are 400 to 520 nm (40 W/m^2) and 355 nm (56 W/m^2). The maximum absorbance found for the used glass was below 340 nm. Wavelengths up to 650 nm might be still effective. UV-A seems to cause mainly membrane damages and molecular and respiratory alterations. Susceptibility to UV increases with age in **Fusarium**, as opposed to **E. coli** where it diminishes.

3-17. Jagger, J. (1976). Effects of Near UV Radiation on Micro-organisms, **Photochem. Photobiol.** 23: 451-454.

(BG, PSE)

Most of the biological important molecules absorb radiation in the near-UV range (300-380 nm). Due to this the lethal effect is more pronounced below 320 nm, and even ten minutes of exposure to bright sunlight will cause a sensible growth delay. Especially affected are the following processes and bio-molecules: respiration, transport across membranes, nucleic acids and the synthesis of proteins.

3-18. Jagger, J. (1981). Yearly Review: Near UV Radiation Effects on Micro-organisms, **Photochem. Photobiol.** 34: 761-768.

*** (BG, PSE)**

Sublethal effects caused by near-UV irradiation on micro-organisms, expressed in a sensible growth delay, are obtained at 20 kJ/m^2 for 334 nm and at 100 kJ/m^2 for 366 nm. The killing and mutational effect is oxygen dependent if the wavelength is greater than 313 nm, but the growth phase of the tested micro-organism will influence its overall sensitivity to near UV.

Peaks of maximum absorbance are found at 340, 410 and 500 nm. The membrane transport processes will be especially affected at 280 and 366 nm, independently of the DNA damage. DNA shows low absorbance up to 350 nm. Synergic interactions are found between near UV (340 nm) and hydrogen peroxide. Other synergic and antagonic interactions between near and far UV are significant at 334, 365 and 405 nm, but need further research.

3-19. Jagger, J. (1983). Physiological Effects of Near UV Radiation on Bacteria. In: K. Smith (Ed.) **Photochem. and Photobiol. Reviews**, Vol. 7, Plenum Press, New York: 1-77.

(BG)

A review of the effects of near-UV light on bacteria is made, focusing on chromophores, sublethal effects, lethal effects and interactions between different wavelengths.

A much more updated review was published later (see # 2-2, Jagger (1985) in this bibliography).

3-20. McCambridge, J. and McMeekin, R. (1981). Effect of Solar Radiation and Predacious Micro-organisms on Survival of Fecal and other Bacteria, **Appl. Env. Microbiol.** 41: 1083-1087.

(MDC)

Solar radiation and microbial predators act synergycally in estuarine water, but the radiation did not affect the predators. It is reported that **Klebsiella pneumoniae** was more sensitive to sun than **E. coli**, which in turn was more sensitive than **Salmonella typhimurium, Streptococcus faecium, Enterobacter aerogenes** and **Erwinia herbicola**.

3-21. Moss, S. and Smith, K. (1981). Membrane Damage Can Be a Significant Factor in the Inactivation of **E. coli** by Near UV Radiation, **Photochem. and Photobiol.** 33: 203-210.

*** (BG, PSE)**

Near-UV inactivation of **E. coli** is inversely related to the concentration of inorganic salts in the medium. It is reported that a decrease of salts increases **E. coli**'s sensitivity to other substances, salts and near-UV. Membrane damage under aerobic conditions, seems to be responsible for this effect.

3-22. Peak, M.J. et al (1987). Inactivation by Monochromatic Near UV Radiation of an **E. coli** hem A8 Mutant Growth with and without d-ALA: The Role of DNA vs. Membrane Damage, **Photochem. and Photobiol.** 45: 473-479.

(BG, PSE)

E. coli exposed to an artificial UV-source in media with and without d-amino-levulinic acid (d-ALA) showed that porphyrin derivatives play an important role in near-UV killing and that the damages to the membranes are more critical than the DNA damages.

3-23. Perez, N. and Hazen, T.C. (1988). **In-Situ** Survival of **Vibro cholerae** and **E. coli** in Tropical Coral Reefs, **Appl. Env. Microbiol.** 54: 1-9.

(MDC)

E. coli and **Vibrio cholerae** cultures enclosed in membrane chambers were kept below sea surface near to coral reefs and in sand for five days. The inactivation rate was studied and **E. coli** was more sensitive than **V. cholerae**, therefore it was not found to be a good indicator of faecal contamination of tropical seawater.

3-24. Qualls, R.G. et al (1984). Comparison of Methods of Enumerating Coliforms after UV Disinfection, **Appl. Env. Microbiol.** 48: 699-701.

*** (MDC)**

Tests were conducted for comparing most-probable-number (MPN) and standard one-step membrane filtration procedures for enumerating coliforms of ultraviolet-disinfected wastewater effluents. It was found that both bacteriological techniques are comparable in their performance and results.

3-25. Rice, E.W. and Hoff, J. (1981). Inactivation of **Giardia lamblia** Cysts by UV Irradiation, **Appl. Env. Microbiol.** 42: 546-547.

(MDC)

Giardia lamblia cysts were exposed to UV radiation and it was found that they were resistant to high doses (less than 90% reduction was obtained with a dose of 63000 uW-s/cm^2). As a comparison, a 99.9% inactivation of **E. coli** was achieved at 3000 uW-s/cm^2.

3-26. Sammartano, L. and Tuveson, R.W. (1985). Hydrogen Peroxide Induced Resistance to Broad Spectrum Near UV Light (300 400 nm) Inactivation in **E. coli. Photochem. and Photobiol.** 41: 367-371.

(BG, PSE)

Cultures of **E. coli** treated with hydrogen peroxide before they were exposed to near-UV radiation, showed an increased resistance to the photo-killing effect of UV.

3-27. Sharp, D.G. (1939). The Lethal Action of Short UV Rays on Several Common Pathogenic Bacteria, **J. Bact.** 37: 447-460.

*** (MDC)**

Ultraviolet induced killing of pathogens is known since the late 19th. century and it has often been used for disinfection of air.

Tests were conducted on several bacteria and the resistance to UV was found to be the following, in increasing order of sensitivity: **Bacillus anthrancis** (less sensitive), **Corynebacterium diphteriae, Staphilococcus aureus, S. hemolyticus, E. coli, Serratia marcescens, Streptococcus hemolyticus, Eberthella typhosa, Streptococcus viridans, Staphilococcus albus** and **Shigella paradysenteriae** (most sensitive).

3-28. Swenson, P. (1976). Physiological Responses of **E. coli** to far UV Radiation. In: K. Smith (Ed.) **Photochem. and Photobiol. Reviews**, Vol. 1, Plenum Press, New York: 269-389.

(BG)

A comprehensive review is made on the effects of far-UV radiation on **E. coli**, focusing on DNA damage and its significance, measurement of cell survival, repair processes and genetics, degradation of nucleic acids, biochemical and physiological aspects, interactions with bacteriophages, growth, etc.

3-29. Tyrrell, R. and Souza, A. (1981). Lethal Effects of Natural Solar UV Radiation in Repair Proficient and Repair Deficient Strains of **E. coli**. Actions and Interactions, **Photochem. and Photobiol.** 34: 331-337.

(BG, PSE)

Solar DNA damage in repair proficient and repair deficient strains of **E. coli** was studied and it was found that an exposure of 20 minutes increased its susceptibility to heat (52°C), MMS (0.1 M) and far-UV.

A representative wavelength of sunlight was found to be 302 nm, more than the usual 254 nm for these type of studies.

3-30. Valdes, L. et al. (1987). Survival of **Candida albicans** in Tropical Marine and Fresh Waters, **Appl. Env. Microbiol.** 53: 1762-1767.

(MDC)

The survival of **Candida albicans** and **E. coli** in tropical seawater and fresh stream water under natural conditions was studied. The conclusions are that both bacteria were not good indicators of faecal contamination because they were able to survive easily in tropical waters, especially **C. albicans**.

3-31. Webb, R. and Brown, M. (1976). Sensitivity of Strains of **E. coli** Differing in Repair Capability to far UV, near UV and Visible Radiations, **Photochem. and Photobiol.** 24: 425-432.

(BRI, BG, PSE)

Deficiencies in DNA repair (excision and recombination) increased the sensitivity of **E. coli** to light, especially to ultraviolet (365 nm) and visible (460 nm) radiations, but did not affect the sensitivity to 650 nm light. The induced lesions appear to be single stranded breaks and a further damage to the repair systems.

The action spectra for lethality showed maximums at 335, 405 and 500 nm. Acriflavine (a repair inhibitor) increased sensitivity.

3-32. Worrest, R. et al (1981). Impact of UV-B Radiation upon Estuarine Microcosmos. **Photochem. and Photobiol.** 33: 861-867.

(BG, PSE)

UV-B radiation (310 nm) was able to penetrate approximately 10% of the upper marine euphotic zone before it was reduced to 1% of its initial value. Natural sunlight with additional UV-B radiation (290 320 nm) caused a decrease of the biomass, of the chlorophyll "a" concentration and the radiocarbon uptake of an aquatic community.

1.4. Physics and Measurement

4-1. Goldberg, B. and Klein, W. (1975). Variations in the Spectral Distribution of Daylight at Various Geographical Locations on the Earth's Surface, **Solar Energy** 19: 3-13.

(BRI)

The spectral quality of sunlight is not the same in different locations on the earth and the rate of its change is not the same, either.

The greatest variations reported are found between wavelengths 600 to 800 nm and 400 to 500 nm. This last variation range seems to be due to local atmospheric conditions. A steady decline of the incident solar energy from 1968 to 1974 at Rockville (Massachussets, USA) is reported.

4-2. Goldberg, B. et al (1979). A Comparison of Some Simple Models used to Predict Solar Irradiance on a Horizontal Surface, **Solar Energy**, 23: 81-83.

(BRI)

Four mathematical models used for predicting solar irradiance are compared: Liu and Jordan (1963), Goldberg and Klein (1978), Reddy (1971) and Barbaro et al. (1978). The

conclusions are that the simplest one is Barbaro's, but Goldberg's is the only one that can be used for daily predictions. Reddy's can not be adapted for daily prediction.

4-3. Goldberg, B. (1982). Radiometric Measurements in the UV-B Region of Daylight. In: J. Calkins (Ed.), **The Role of Solar UV Radiations in Marine Ecosystems.** Plenum Publishing Co: 121-129.

(BRI)

The development and testing of a light-monitoring device is reported. Tests were conducted from 280 to 325 nanometers (nm) in 5 nm bands using interference filters. The reported advantages of this equipment are: low maintenance, simplicity and easily operated in natural environments. Especially recommended for biological experimentation.

4-4. Smith, B. and Tyler, J. (1976). Transmission of Solar Radiation into Natural Waters. In: K. Smith (Ed.): **Photochem. and Photobiol. Reviews**, Vol. 1, Plenum Press, New York: 117-157.

*** (BG)**

The optical properties of fresh and sea water are discussed, placing emphasis on the attenuation coefficient, irradiance coefficient, error causes, measurement units and nomenclature. An extrapolation into the ultraviolet range is made, where little experimental data is available.

2. DIRECTORY

This list is made of the names and addresses of people and institutions of importance to the ongoing and future Solar Water Purification research projects. It might be possible that not all the involved are listed, but all the listed are involved.

Only the updated data are given. For obvious reasons, the names and addresses older than five years are not included, unless a special reason is explained.

2.1. Solar Water Purification Projects

The following list has two parts: first the names and addresses of the researchers involved in the projects on Solar Water Purification sponsored by IDRC, UNU and INRESA/BRI, and second, the names and addresses of the support staff and related investigators. The names are given in alphabetic order.

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2.2. Cited authors

This list is made of the names and addresses of the authors of articles summarized herein, organized alphabetically. To the right, following the name is a very short sentence that describes broadly the current research interests of importance to the Solar Water Purification research projects.

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Goldberg, B. (UV measurement)
See Smithsonian Environmental Research Center in 2.3.2.

Grigsby, P. (UV effects on microorganisms)
See Calkins, J. in this section.

Hader, D. (UV effects on microorganisms)
See Senger, H. in this section.

Hazen, T.C. (Water contamination)
See Perez, N. in this section.

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Narikawa, O.T. (UV effects on microorganisms)
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The following periodicals (organized alphabetically) cover most of the research publications of importance to the Solar Water Purification subject.

Applied and Environmental Microbiology
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Applied Microbiology and Biotechnology
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Appropriate Technology for Health
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ENFO, a quarterly newsletter of ENSIC
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Environmental Sanitation Abstracts
See Environmental Sanitation Review in this section.

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Journal of the Water Pollution Control Federation
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Photochemistry and Photobiology
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3. GLOSSARY

Due to the special and interdisciplinary characteristics of the Solar Water Purification research subject, a condensed and uniform glossary is made of the most important and usual terms.

Absorbance: The amount of radiant energy absorbed by a substance. Inversely and logarithmically related to transmittance.

Aerobic conditions: Situation in which enough oxygen is available for use by living organisms. The opposite to anaerobic conditions.

d-Amino-Levulinic Acid (d-ALA): Important metabolic substance used for the production of porphyrins and many other related compounds.

Amorphous solids: Group of solids without real or apparent crystalline form.

Anaerobic conditions: Situation in which oxygen is not available for living organisms. The opposite to aerobic conditions.

Antagonism: Relation in which one factor (substance, radiation, force, etc.) lessens the effect of another. The opposite to synergism.

Aquatic food-related diseases: Illnesses caused mainly by ingestion or handling of aquatic food sources.

Bacterial density: Amount of bacteria present in a specified quantity of solution or area. Usually expressed as number of organisms per mililiter or per 100 mililiters.

Bacteriophages: Viruses that live within bacteria.

Bio-assay: Experimental technique in which living organisms are used for assessing the effect of a substance.

Biochemical Oxygen Demand (BOD): Amount of dissolved oxygen in an aqueous solution that is consumed by micro-organisms, during the break-down of the present organic substances under standardized conditions (five days, darkness, 20°C).

Biomass: Amount of living matter in an area or volume of space. Also, the amount of organic substances obtained from living organisms.

Blue Light: Radiant energy with a wavelength range between 250 and 450 nm approximately.

Carotenogenesis: Metabolic process of natural or induced synthesis of carotenoids (yellow to red pigments).

Chemical Oxygen Demand (COD): Amount of oxygen needed for the complete break-down of substances found in a solution.

Chloroplast: Cellular organelle in which photosynthesis takes part. Contains the blue-green pigments known as chlorophylls.

Chromophores: Chemical group or substance that gives colour to a compound.

Coliforms: Group of bacteria related to **Escherichia coli** (one of the most abundant components of the intestinal flora).

Cultures: Any pure or mixed group of bacteria grown under laboratory conditions.

Cyst: Resting, dormant or vegetative stage used by some micro-organisms for surviving difficult conditions. Characterized by its high resistance to environmental stress.

Desoxiribo-Nucleic Acid (DNA): Substance found in the chromosomes, responsible for the transmission of genetic characteristics of a living organism. Usually found as a double stranded (dsDNA) chain, but sometimes also single stranded (ssDNA).

Dissolved oxygen: Amount of oxygen found in an aqueous solution. Usually expressed in parts per million (ppm).

Dysenteries: Severe diseases caused by infection and characterized by strong diarrhea with passage of mucus and blood.

Effluent: See Secondary effluent.

Electron Spin Resonance (ESR): Research technique based on the magnetic fields related to electron movements. It is used for studying the physical and chemical characteristics of a compound.

Endemic: Living organisms or diseases restricted or peculiar to a region.

Enteric: Of or relating to the intestines.

Entero-pathogenic: Disease causing organisms of intestinal origin.

Estuarine water: Waters of a sea region where salt and fresh water mix.

Exposure time: Or residence time, is the amount of time (minutes) that a quantity of water is exposed to sunlight in a flow-through system.

Euphotic zone: Region of a water body where enough light is available for the growth of plants.

Far ultraviolet: Ultraviolet radiation with a wavelength range of 200 280 nm approximately. Also known as germicidal radiation or UV-C.

Flow-through system: Solar Water Purification system developed by A. Acra et al. in which a large amount of water is continuously exposed to sun, as it flows through a transparent tube.

Fluence: Solar energy intensity received by an object during a certain amount of time (exposure time). Also known as radiation dose. Expressed in uW-s/cm^2 or W-hr./m^2 and similar units.

Gastroenteritis: Infection and inflammation of the lining membranes of the stomach and intestines, characterized by severe loss of fluids.

Germicidal action: Inactivation or killing effect exerted by a chemical or physical factor on pathogens.

Haloforms: Related to or formed by halogens.

Halogens: Group of five chemical elements with similar characteristics: chlorine, iodine, fluor, bromine and astatine.

Halosol disinfection: Bacteriological purification of a solution by the combined application of halogens and solar energy.

Indicator bacteria: Group of bacteria used for assessing the quality of a water body (usually faecal **E. coli**).

Intensity: Amount of incident radiation. Expressed in uW/cm^2, W/m^2 and similar units.

Interactions: Effect relationships among two or more chemical, physical or biological factors. Usually two main types are recognized: antagonism and synergism.

International Drinking Water Supply and Sanitation Decade: Installed in 1980 by the World Health Organization, it aims at providing safe drinking water supplies and sanitation facilities to all mankind by 1990.

Irradiation: Exposure to a radiation source.

Lethal effects: Inactivation or killing of a group of organisms (usually bacteria in these publications) by a chemical or physical agent.

Media: Usually the mix of different substances used for growing a group of micro-organisms.

Metabolism: Group of bio-chemical reactions that take place in a living organism in order to produce energy or specific substances.

Mid ultraviolet: Ultraviolet radiation with a wavelength range of 280 320 nm approximately. Also known as UV-B, sunburn or erythemal radiation.

Molarity (M): Expression of the concentration in number of moles of solute per liter of solution (mol/l).

Morbidity: The relative incidence of a disease on a population.

Mortality: The proportion of deaths in a population due to a specific cause, usually diseases.

Most Probable Number (MPN): Expression and technique for estimating the bacterial density of a sample.

Near ultraviolet: Ultraviolet radiation with a wavelength range of 320 400 nm. Also known as black light or UV-A.

Non-coliforms: Group of bacteria without similarity to the **E. coli** resembling group.

Nucleic acids: Group of substances (DNA and RNA) related to the transmission and expression of the genetic characteristics of a living organism.

Optical absorption: See Absorbance.

Pathogens: Disease causing organisms, usually bacteria, viruses and larger parasites.

Percentage (%) solution: Expression of the concentration of a solution usually in grams or mililiters of solute per 100 mililiters of solution.

pH (potential of Hydrogen ions): Logarithmic expression of the concentration (molarity) of hydrogen ions in a solution, with a scale ranging from 0 or 1 (very acid) to 14 (very alkaline).

Phages: See Bacteriophages.

Photo-dechlorination: Elimination by sunlight of chlorine residuals from a treated solution.

Photo-dehalogenation: Elimination by sunlight of halogen residuals from a treated solution.

Porphyrin: Group of metabolic substances with biochemical and photo-biological important characteristics like chlorophyll, bilirrubin and hemoglobin.

Potable water criteria: Water for drinking purposes must be: free of pathogens and pathogenic substances, clear, non-saline, without taste or smell and non-corrosive. Specific criteria vary from place to place, but usually less than 10 coliforms/ml and less than 5 **E. coli**/ml are bacteriological required criteria. Water used for washing or bathing purposes has to meet less exigent criteria.

Prevalent: Most important, widespread or dominant disease or pathogen.

Repair-deficient strain: Group of organisms (bacteria) very sensitive to damages in their nucleic acids because of lack of their repairing enzymatic systems. Opposite to repair-proficient strain.

Residence time: See Exposure time.

Respiration: Group of biochemical reactions that require and consume molecular oxygen in order to produce energy.

Ribo-Nucleic Acid (RNA): Group of nucleic acids (usually single stranded, ssRNA) related to the expression of genetic characteristics. In some micro-organisms they

are also involved in the transmission of these characteristics and can be double stranded (dsRNA).

Secondary effluent: Effluent from wastewater treatment plants after the primary (filtering) and secondary (removing) processes took place.

Sensitizing agent: Substance that increases susceptibility to radiation, usually sunlight.

Solar box cooker: Special designed box that absorbs and concentrates solar energy for cooking purposes.

Solar energy: All kind of radiation from the sun that reaches the earth, usually after being scattered and filtered through the atmosphere. Divided into invisible (ultraviolet and infrared) and visible ranges.

Solar irradiance: See Intensity.

Solar irradiation: Emission of or exposure to solar radiation.

Solar Water Disinfection: Simple technique of water potabilization or purification for drinking purposes, developed by A. Acra et al. in Beirut (Lebanon) since the late 70s, in which the polluted water sample is exposed to the effects of sunlight for a certain time.

Solar Water Potabilization: See Solar Water Disinfection.

Solar Water Purification: See Solar Water Disinfection.

Spectrophotometry: Research technique based on the amount of radiant energy absorbed or transmitted by a substance, used for studying its composition, concentration and other chemical and physical properties.

Spore: Vegetative and reproductive stage of an organism, characterized by its resistance to environmental stress.

Sublethal effects: Transitory reduction of growth and reproduction of a bacterial group, due to minor damages caused by a chemical or physical agent.

Suspended solids: Amount of solids in an aqueous solution with an overall size between 10 and 100 um, approximately, that do not settle easily.

Swaband Count Technique: Bacteriological technique developed by Double Integral Sanitation Ltd. (Mississauga, Ontario, Canada) used for estimating bacterial density.

Synergism: Relationship between two or more chemical, physical or biological factors, in which the effects of each one is added to or increases the effect of the other(s).

Total bacteria: Total number of bacteria present in a specified amount of solution or area. Usually expressed in numbers per mililiter or per 100 mililiters.

Total heterotrophic bacteria: Number of bacteria that are not able to synthesize their own food, present in a specified amount of solution or area.

Total organic carbon content: Total amount of carbon from organic substances, present in a sample.

Transmittance: Usually the percentage of incident radiation that passes through a substance. Inversely and logarithmically related to absorbance.

Ultraviolet A: See Near ultraviolet.

Ultraviolet B: See Mid ultraviolet.

Ultraviolet C: See Far ultraviolet.

Ultraviolet light: See Ultraviolet radiation.

Ultraviolet radiation: Radiation with a wavelength range of 3 - 400 nm approximately, usually originated by the sun and divided into four categories: extreme, far, mid and near UV.

Vegetative forms: Highly resistant stages of growth or reproduction of some micro-organisms, used for surviving difficult environmental conditions.

Water-associated diseases: See Water-related diseases.

Water-based diseases: Diseases in which the pathogen spends part of his life cycle inside an intermediate aquatic organism before infecting the final host (usually human).

Water-borne diseases: Diseases caused by pathogens that are disseminated by contaminated water, without intermediate hosts.

Water-related diseases: All kind of diseases in which the pathogen is disseminated through water, an intermediate aquatic host or by a water related carrier. Also known as water-associated diseases.

Water-related insect-mediated diseases: Diseases caused by pathogens that are transmitted by carriers which are related to water. The pathogen itself has no relation to water.

Water-washed diseases: Diseases caused by lack of water that facilitates an easy transmission of pathogens.

Wavelength (λ, lambda): Distance (in nanometers) between two subsequent waves of a radiation.

4. LIST OF ABBREVIATIONS

d-ALA: delta-Amino-Levulinic Acid.
AUB: American University in Beirut (Lebanon).
AUC: American University in Cairo (Egypt).

BG: Botany and Genetics Library of McGill University.
BOD: Biochemical Oxygen Demand.
BRI: Brace Research Institute of McGill University.
BW: Blacker Wood Library of McGill University.

°C: Degrees Celsius of temperature.
COD: Chemical Oxygen Demand.
cal/cm^2: calories per square centimeter.

DNA: Deoxyribonucleic Acid.
dsDNA: double-stranded DNA.
dsRNA: double-stranded RNA.

ENSIC: Environmental Sanitation Information Center.
ESR: Electron Spin Resonance.
uE/m^2-s: micro-Einstein per square meter per second.

°F: Degrees Fahrenheit of temperature.
FFF: Family spacing, Food supplements and Female education.

GOBI: Growth monitoring of young children, Oral rehydration therapy, promotion of Breast feeding and Immunization.

INRESA: Integrated Rural Energy Systems Association.
IDRC: International Development Research Centre.
IR: Infrared radiation.
IWEC: International Water Engineering Center.

kJ/m^2: kilo-Joule per square meter.

λ : lambda (wavelength).

M: Molarity (moles of solute per liter of solution)
um: micro-meters (10^{-6} meters)
MD: Medical Library of McGill University.
MDC: Macdonald College Library of McGill University.
MPN: Most Probable Number of bacteria.

nm: nanometers (10^{-9} meters).

OD: Outer Diameter.
ORS: Oral Rehydration Solution(s).
ORT: Oral Rehydration Therapy.

%: percentage (in g/100 ml for solutions).
pH: potential of Hydrogen ions (measurement of acidity and alkalinity).
ppb: parts per billion (micrograms per 1000 l).
ppm: parts per million (micrograms per liter).
PSE: Physical Sciences and Engineering Library at McGill University.

RNA: Ribonucleic Acid

ssDNA: single-stranded DNA
ssRNA: single-stranded RNA.

UNU: United Nations University.
UV: Ultraviolet radiation (100-400 nm).
UV-A: Near-UV (320-400 nm).
UV-B: Mid-UV (280-320 nm).
UV-C: Far-UV (200-280 nm).

VIS: Visible light (400-680 nm).

W/m^2: Watt per square meter.
$kW\text{-}hr/m^2\text{-}day$: kilo-Watt per hour per square meter per day.
kW/m^2: kilo-Watt per square meter.
uW/cm^2: micro-Watt per square centimeter.
$uW\text{-}s/cm^2$: micro-Watt per second per square centimeter.
WHO: World Health Organization.
WUSC: World University Service of Canada.

5. INDEXES

5.1. Name Index

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